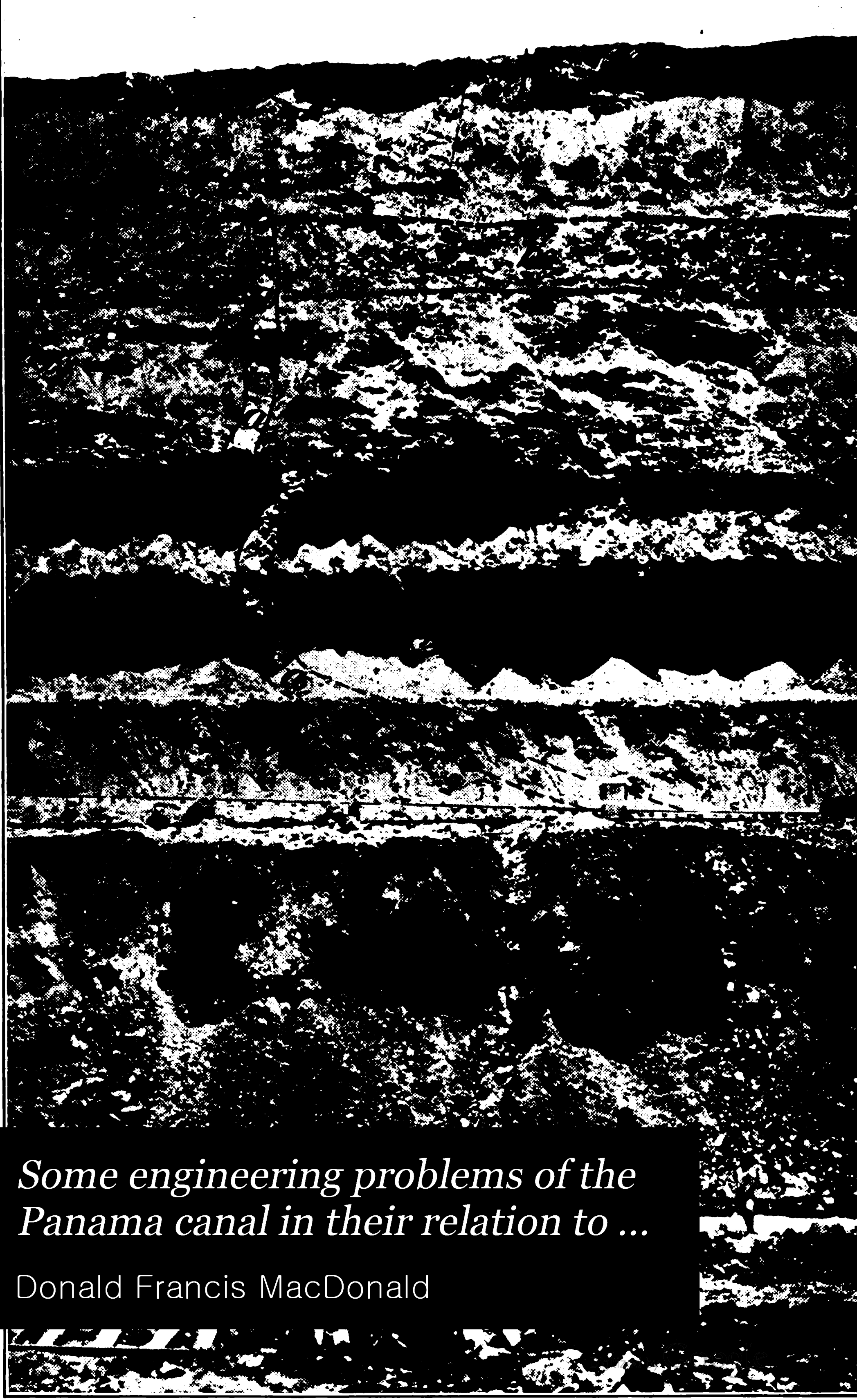

DEPARTMENT OF THE INTERIOR

Bulletin 86

DEPARTMENT OF THE INTERIOR

FRANKLIN K. LANE, SECRETARY

BUREAU OF MINES

VAN. H. MANNING, ACTING DIRECTOR

SOME ENGINEERING PROBLEMS OF THE PANAMA CANAL IN THEIR RELATION TO GEOLOGY AND TOPOGRAPHY

PUBLISHED WITH THE APPROVAL OF THE GOVERNOR OF THE PANAMA CANAL

BY

DONALD F. MACDONALD

Very Valuable Document.

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CONTENTS.

ILLUSTRATIONS.

SOME ENGINEERING PROBLEMS OF THE PANAMA CANAL IN THEIR RELATION TO GEOLOGY AND TOPOGRAPHY.

By Donald F. MacDonald.

INTRODUCTION.

This report aims to discuss, from the viewpoint of the mining geologist, the bearing of topographic and geologic conditions on certain problems that arose in the construction of the Panama Canal. It is published by the Bureau of Mines as a contribution to engineering literature because it presents information that shows how geology and topography must be considered by the mining engineer in planning excavations and in removing loose material and solid rock in the safest and most efficient manner.

The printing of this bulletin has been approved by the governor of the Panama Canal, as it was impracticable for the Panama Canal to give this information to the general public in any of its publications.

The "sword cut" of Goethals and his men did not sever the Isthmian barrier; it merely clove the hills to a depth of 40 feet above sea level. This cut and the great areas of low valleys at both ends of it have been covered with fresh water to the 85-foot level. This high-level lake held by dams at either end, the 85-foot locks by which ships enter it, and the dredged approaches from the two oceans constitute the Panama Canal.

In the preparation of accurate estimates concerning the cost of large excavations information regarding the geologic conditions, as obtained by a study of natural features, is necessary. Drill holes and test pits will furnish supplementary geologic information, but without a general knowledge of the geologic conditions it will not be possible for the constructing engineer to answer such questions as the following: (1) What rock units will be encountered in the excavation and in what proportion? (2) What will be the cost of drilling each for blasting? (3) How far apart and how deep must the drill holes be to efficiently break the rock of each to the proper size—not too fine nor yet too coarse? In this connection jointing, fissuring, bedding, toughness, and other physical characteristics must be considered (4) How steep will the slopes of the excavation stand, and to what extent will they wash and trench on exposure to the atmosphere?

(5) What proportion of the material to be excavated is of such physical character that it may be utilized in any other part of the project, such as in concrete construction, road making, wharves, breakwaters, riprap work, etc.?

ACKNOWLEDGMENTS.

The first work of considerable scope bearing on isthmian geology was that of Hill [a] in 1895.

In 1899 Bertrand and Zurcher [b] published a brief report on the geology of the Isthmus for the New French Company (Compagnie Nouvelle du Canal de Panamá).

In July, 1906, Howe [c] was sent to the Isthmus by the new American canal commission to report on such phases of engineering geology as lock and dam foundations and the natural resources of the country. Again, from January to April, 1907, he spent some time on the Canal Zone. His reports are most interesting. Other publications bearing on isthmian geology are listed in the bibliography given at the end of this bulletin. Hill, Howe, and the earlier workers must be congratulated on the results they obtained, in view of the shortness of the time at their disposal, the few and small excavations then made, the thick soil, and the jungle that obscured much of the land at that time.

In 1910, as Culebra Cut was deepened, great masses of earth and rock began to crush down from its slopes. It was thought well to have these and other phases of the work that had a geological bearing studied by a geologist. To make recommendations on this question C. W. Hayes,[d] then chief geologist of the United States Geological Survey, was, at the instance of the Secretary of War and Secretary of the Interior, sent to the Canal Zone. He realized that certain geological principles underlay the slides and recommended that a geologist be appointed to study them.

For this work the writer, who had been assistant geologist of the United States Geological Survey, was sent to the Isthmus, January, 1911, as geologist to the Isthmian Canal Commission. To this commission and to members of the engineering staff, but particularly to Col. George W. Goethals, chairman and chief engineer, the writer is indebted for wide opportunity to make geological studies and for suggestion and interest in results.

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[a] Hill, R. T., Geological history of the Isthmus of Panama and portions of Costa Rica: Bull. Museum Comparative Zoology of Harvard College, vol. 28, 1898.

[b] Bertrand, M., and Zurcher, P., Étude géologique sur l'Isthme de Panama; Rapport de la Commission. Compagnie Nouvelle du Canal de Panama, vol. 1, 1899, pp. 85–120.

[c] Howe, Ernest, Canal Commission Ann. Report 1907, Appendix E, pp. 108–138; Isthmian geology of the Panama Canal: Econ. Geol., vol. 2, 1907, pp. 639–658; Geology of the Isthmus of Panama: Am. Jour. Sci., vol. 26, ser. 4, 1908, pp. 212–237.

[d] Hayes, C. W., Notes on the geology and slides of Culebra Cut: Canal Record, vol. 4, Dec. 7, 1910, p. 115.

RELATION OF DIFFERENT FACTORS TO ENGINEERING PROBLEMS.

TOPOGRAPHIC TYPES.

What topographic conditions confronted the builders of the Panama Canal? The surface configurations of that part of the Isthmian land barrier that is within the Canal Zone fall under two chief types. They are: (1) The hill type of topography, developed in the interior and locally on the Pacific side and consisting chiefly of irregular angular hills, short ridges, and crooked unsymmetrical valleys and basins (Pls. I and II); and (2) the coastal-plain type, developed as low hills and swampy flats in the vicinity of Colon and locally on the Panama side (Pl. III)

HILL TYPE.

The hill type of topography is well developed in the central and southern parts of the Canal Zone. Cerro Gorda, near Culebra, and Cerro Balboa, near the old site of Gorgona, stand approximately 1,000 feet above sea level, and below this elevation are many lesser peaks. Seen from a position of commanding view, this topography is most striking in its irregularity and presents some likeness, in its green jungle-covered irregular hills and hollows, to enormous cross waves at sea. It is a type of land form not uncommon in the Republic of Panama.

Now, what relation does this type of topography have to canal construction? In building the Panama Railroad and in building some of the dirt-train and other branch lines connected with canal construction the numerous hills had, of course, to be avoided, with the result that the sinuosity of the tracks added difficulties both to their construction and operation. The new line of the Panama Railroad is relatively little curved, but it encountered some heavy cuts and fills. The canal passes between Gold Hill, 662 feet high, and Contractors Hill, 450 feet high, and a part of each had to be removed in the digging of Culebra Cut, thus adding to the amount of excavation. Conditions had to be studied in choosing the route, so as to strike the proper balance between minimum excavation and minimum curvature of the canal channel. On the other hand, most of the hills are composed of tough hard rock which could not readily be worn away and cut into valleys by the streams. This stronger rock forms Gold and Contractors Hills, and these are strengthening pillars which hold back slides of weaker rocks. Ancon Hill, another high point of hard rock, furnished a convenient quarry for stone to be crushed and used in the concrete of the Pacific locks. The height and steepness of Ancon Hill is such that the whole rock product could be handled by gravity from the quarry, through the crushing plant, and then

into cars. The site of another quarry near Frijoles was first picked out by the writer from a railroad train because of its steep ridge-like topographic expression. On further exploration the ridge was found to be composed of basalt, but the rock was a little too much jointed for the desired use, the facing of a breakwater. The hills and higher areas, because of their steep slopes, contain no stagnant water in which mosquitoes and other pests can breed, and have good drainage, hence, where convenient, they were utilized as camp sites. By clearing the jungle cover off the tops of the higher hills they became convenient triangulation stations for the surveys of the Canal Zone. Plate IV indicates the location and area of the hilly region, which is practically coextensive with the areas of igneous rocks, and Plates I and II convey some idea of its character.

COASTAL-PLAIN TYPE.

Coastal plains locally border both the Atlantic and the Pacific coasts of Central America. In the Canal Zone this type of land form is principally on the Atlantic side and comprises five kinds of subtypes. They are: (1) Coastal swamps, of considerable depth, composed of soft dark mud and organic matter, and inland swamps and alluvial basins; (2) coral reefs, awash at half tide, and coral flats, composed largely of coral débris, slightly above high-tide level; (3) river flats of alluvium in the lower valleys; (4) bars at and near the mouths of rivers, beaches, sand spits, etc.; (5) seaward-tilted relatively smooth plains, low hills, and higher dissected remnants of former plains. A discussion of the origin of the land forms of the isthmian region is not within the scope of this report.

The first practical relation between the engineering work and this type of topography was the great difficulty of making surveys through the unhealthful black-mud and green-water swamps. Next came the construction of the Panama Railroad lines across the swamps. A feature of this construction was the necessity of vast fills with wide bases. The extra width was to obviate the sinking of the fill, with accompanying bulging of the swamp material on either side of the sunken part. Another most important matter was the building up of a great coral flat from its original high-tide level to 3 or 4 feet above, in order to furnish a site for the town of Colon and the Atlantic terminal plant of the canal and the Panama Railroad. On the other hand, the flats formed mostly of coral débris, unlike the swamps, presented a solid foundation on which to dump spoil, and thus to build up and prepare a solid base for the town. The low mud swamps and river alluvium greatly facilitated the dredging of the approach channels to both the Atlantic and the Pacific locks.

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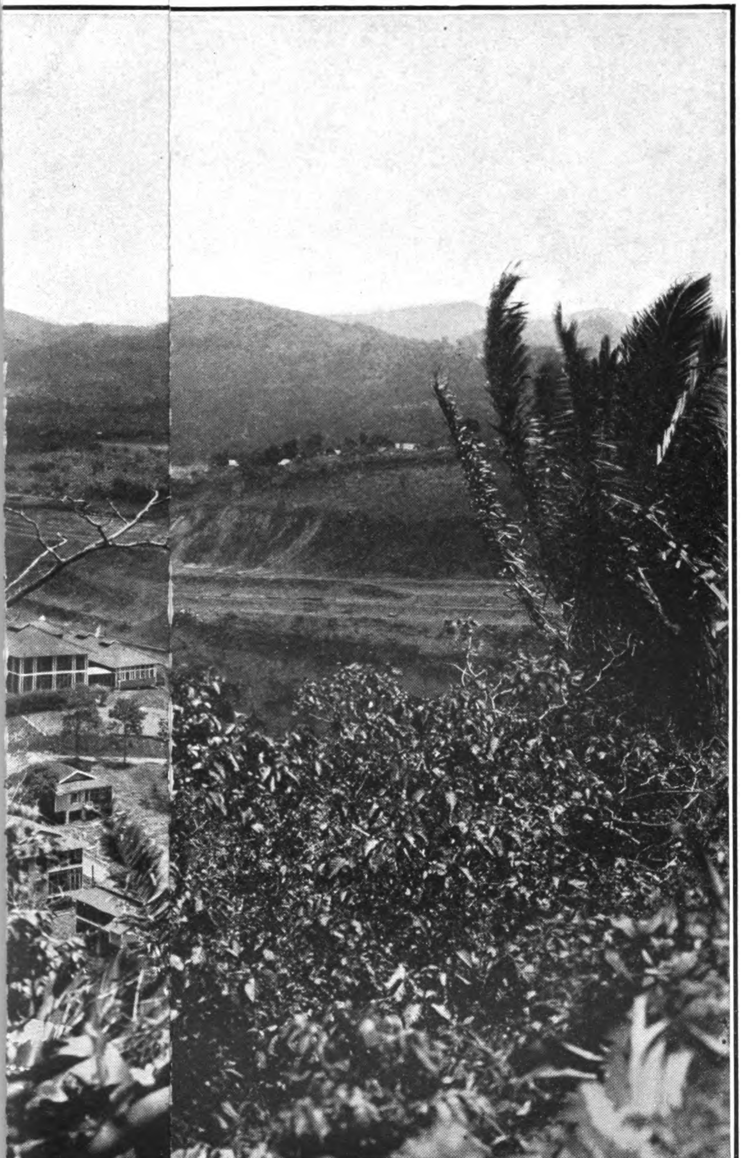

KING NORTHW

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CLIMATE.

In computing the cost of any engineering project due weight should be given to the effect of climatic conditions on labor efficiency and also on construction plans.

RANGE OF TEMPERATURE.

The Canal Zone has a moist tropical climate, modified by oceanic conditions, and therefore showing little yearly and daily variation of temperature. The nightly average is 71° and the daily about 85° F. The daily range of temperature is greatest in the dry season, for then there are few clouds to obscure the sun's heat in the day or to absorb and reflect the radiation from the earth at night. The highest recorded temperature over a number of years is 97° F., observed at Ancon February 13, 1906, and the lowest 59° F., observed at Bas Obispo February 9, 1907.

RAINFALL.

On the Canal Zone there are two seasons—one short and relatively dry, the other long and wet. The dry months are January to April, inclusive; the other months are wet. The wettest period is from September to December. Most of the rain falls during the day, between 10 a. m. and 4 p. m., but may fall at any time. The average yearly precipitation over a number of years for Panama is as follows: Ancon or Panama City (Pacific side), 71 inches; Culebra, 90 inches; Monte Lirio, 135 inches; Colon, 129 inches; Porto Bello, 170 inches.

Tropical conditions generally add to the cost of engineering work, from causes as follows: (1) Inefficiency of native labor; (2) inefficiency of imported labor working under tropical conditions; (3) cost of sanitation; (4) loss of time during heavy rains; and (5) hindrance to engineering works through floods, etc. These factors added many million dollars to the cost of the canal. They are all discussed at some length in the annual reports of the Isthmian Canal Commission.

AGRICULTURAL AND FOREST PRODUCTS.

The question of subsistence for the vast army of canal employees was, of course, a vital one. It was found that American vegetables could not be profitably grown in the Canal Zone. In fact, most of them, as well as oats, wheat, barley, and most kinds of American grasses, could scarcely be grown at all. Hence, these products were imported from the United States. A great cold-storage plant was established at Colon, with smaller distribution plants along the zone. In this way fresh meats, vegetables, and fruits were brought in and distributed in prime condition. The inventors of canned goods and cold storage were certainly heavy contributors to the campaign of canal construction.

The hill land of the Canal Zone will never have much agricultural value, even for tropical products, because of the steepness of the slopes and the shallowness of the soil. The steep land if cultivated would wash rapidly in the heavy tropical rains of that region. A subsequent discussion of the effect of streams brings out the fact that erosion took place in the upper parts of stream valleys, whereas deposition of gravel, sand, and silt was the dominant process in the lower ends. Now, in nearly all countries the broad flood plains that have been built by deposition of rich silty soil are especially adapted for agriculture. The flood plains of the Chagres, Trinidad, and Gatun Rivers contained much rich land suitable for growing bananas, tobacco, and sugar cane. However, they also contained pools of stagnant water that afforded breeding places for mosquitoes and other pests, and hence were considerably more unhealthful than the higher ground. Much of this alluvial land has now been covered by Gatun Lake, and what remains will probably never have value commensurate with its richness of soil because of the depressing climate and the malarial conditions that prevail.

Most of the timber within the Canal Zone was cut years ago, so that nearly all the lumber needed for building the "construction-camp" towns had to be imported. Some of the ties for the Panama Railroad were made by natives from extremely resistant native woods, such as guyacan (or false lignum-vitæ) and níspero, or balata tree (*Mimusops darinensis* Pittier). The name, however, is also applied to other trees of the same family. For making dugout canoes the natives use chiefly espavé (*Anacardium rhinocarpus* D. C.), cedro, or Spanish cedar (*Cedrela* sp. pl.), and pochote (*Bombax Barrigon* Seem.). In general, the forests were more of a hindrance to the work than otherwise, for they formed a thick jungle through which many survey lines had to be cut and clearings made for roads, trails, reservoirs, and town sites.

STREAMS.

The heavy precipitation is evidence that the country must be well watered. The Chagres, which flows for a part of its course through the Canal Zone, is the chief stream (see Pl. IV). It has a relatively large catchment basin, the slopes of which are locally steep; hence during heavy rains the volume of its flow is vastly increased, only to shrink greatly during the dry season. Trickling streams swell into destructive torrents after long and heavy rains. The percentage of absorption during the wet season is relatively small because the covering of porous soil, especially on the higher land and steep slopes, is very thin, and most of the rocks, except the river alluvium and gravels, the conglomerates, and sandstones, are exceedingly fine grained and have relatively little pore space or

COASTAL-PLAIN TYPE OF TOPOGRAPHY.

Flat lands near Mount Hope, with some small knolls, or rounded hills, rising 10 to 50 feet above the general low flat surface of the plain. This group of small knolls has been called the Monkey Hills. The hills are remnants of a higher land surface; the interhill areas having been washed away by stream erosion when the isthmian land stood some hundreds of feet higher than now. *a*, A knoll rising about 30 feet above the surrounding plain.

water-containing capacity. Then, too, the rainfall is so heavy that the ground is soon saturated and the percentage of run-off becomes high.

The streams on their way to the ocean pass through three general stages of size and activity. In the first stage the stream is small and flows swiftly down the gradient of a steep valley, carrying along bits of soil and rock from the surface over which it passes. In the second stage the stream is less swift but much larger, having been reinforced by many smaller influents. Because of its greater volume its carrying capacity is greater, and bowlders, cobbles, and gravel are rolled along its bottom, grinding each other as they go, and thus manufacturing finer and more easily transported material. The third and last stage is that in which the stream flows through a wider, flat, and almost base-leveled valley, on the last course of its oceanward journey. The water now moves with comparative slowness, hence can carry only the finest sediments and is forced to deposit part of its load.

The wide lower part of a stream valley is generally called a flood plain, for it is flooded during very high water and receives a small building-up increment of sediment from each flood. The heaviest deposition of sediment is along the line where the river overflows its banks, because the current is materially slowed down along this line. The ground is therefore built up higher near the river bank, and in this way what are termed "natural levees" are formed. The finer sediment is often held in suspension until the river current is checked when it reaches the sea. The sediment then, if not carried away by tidal currents, falls to the bottom at or near the river mouth to form bars or shoals.

RELATION OF STREAMS TO CANAL CONSTRUCTION.

The streams of the Canal Zone have a most vital relation to the canal, because they furnish the water to fill the dammed-in part of the waterway between the locks (see Pl. IV). Without the streams only a sea-level canal would be possible. The damming of the streams originated Gatun Lake and caused the backwater to fill Culebra Cut to navigable depth. The waste water from Gatun Lake will operate an immense hydroelectric plant which is to supply the whole Canal Zone with light and electric power, and is to be used to electrify the Panama Railroad. In the building of the railroad, roads, etc., and in some of the concrete construction and other work incidental to canal construction, it was found that gravel served the purpose almost as well as crushed rock and was much cheaper.

The general method by which streams roll rock fragments and bowlders along their bottom in their swifter upper courses and gradually grind them into gravel, and how they deposit the gravel where their velocity slows down somewhat and carry the finer silts down to

their flood plains and to their mouths has already been discussed. The streams may, therefore, be looked upon as great gravel and silt manufacturing and sorting plants. They, of course, turn out and classify material vastly cheaper than the rock-crushing plants can. The Gamboa Bridge of the Panama Railroad crosses the Chagres River well above the normal flood plain, in the gravel-dumping zone of the river, and hence is convenient to bars of good ballast and gravel for construction work. In this important item the streams contributed directly to the construction of the canal. On the other hand, because of the liability to floods in the streams, it has been necessary to have the bridges spanning them extra strong, and therefore more expensive.

VALLEYS.

When water flows over a land surface it follows the line of least resistance, not only so far as the gradient is concerned, but also in respect to the ease with which it may erode a channel for itself in the material over which it passes. It thus tends to do minimum erosive work on the resistant areas of rock, so that in time these are left as remnants or hills between the streams. The softer rocks, being more susceptible to stream erosion, become the sites of valleys. In this way, through geologic time, the Obispo River and its tributaries kept wearing down the drainage outlet from the Culebra Basin, thus lessening the excavation work necessary for the future Culebra Cut. The Chagres, the Gatun, the Trinidad, and their tributaries kept excavating valleys that are now the site of the great Gatun Lake. The Rio Grande River Valley and its tributary valleys were utilized, for these streams had centuries ago begun the excavation of what man has now elaborated into the south end of Culebra Cut, the Miraflores Lake, the terminal port, and the dredged out approaches to the locks on the Pacific side. Not only in the making of the canal, but in the building of the railway lines, the water and sewage systems, etc., the valleys were utilized as far as possible.

BAYS, HARBORS, AND SHORE CONDITIONS.

Several features of the bays and harbors of the Canal Zone have involved engineering problems. Of these the relative shallowness of Colon and Panama Bays and the natural exposure of Colon Bay to northerly winds, and the Pacific entrance of the canal to southerly winds are the most important. In order to make these bays more sheltered and safe for ships, great breakwaters have had to be built.

Now come such practical questions as: Are Colon and Panama Bays likely to grow more shallow so that much dredging will be necessary to keep them navigable, or will the ship channels in them gradually become deeper from tides and shore currents? It might also be

asked why Panama and Colon Bays are relatively shallow, whereas Porto Bello Harbor, not far distant, is about 60 feet deeper.

The shallow bays are the slightly submerged margins of the adjoining flat shore area. In relatively recent geologic time (Pleistocene) these bay areas were dry land. Approximately, the same gentle seaward slope of the land is maintained below the water level of Colon Bay out to the edge of the continental shelf as occurs above it, except for the marginal coral reefs and flats that form a wedge-shaped fringe around the present shore line. This fringe of limy rock and coral is about 35 feet thick at its outer edge and rests on the normal rock bottom. It locally presents an abrupt face to the sea and its outward margin is a few feet below high-tide level. There are also a few low headlands with steep slopes formed by the erosive action of sea waves on some of the points of higher land. Toro Point, 50 to 60 feet above sea level, is one of these.

The land surrounding Porto Bello harbor is steep and mountainous, and its slopes continue relatively steep down to the flat bottom of the harbor about 90 feet below the surface of the water. In the upper end of this harbor, however, considerable silt has been dumped by streams. Two other factors have made both Panama and Colon Bays more shallow, while they have had relatively little effect on the deep harbor of Porto Bello. They are: (1) During the rainy season all streams are swollen to great size, and they come down red and mud-colored from their load of sediment. When they reach the ocean the sediment is deposited, as already explained, and each year a thin layer of silt is left on the bottom of the bay into which they empty. In the time since this process began enough silt has been deposited to make the water considerably shallower. (2) In very recent geologic time the whole land mass has risen, as proven by old beach marks of fresh appearance, which, near Colon, are about 6 feet above sea level, and on the Panama side are a little higher. This rising has left Colon Bay about 1 fathom and Panama Bay more than a fathom shallower than they were previously. This recent rise of isthmian land, which reached a maximum of about 30 feet in Los Santos Province, probably took place within the last 1,000 years, according to evidence in hand. In fact, it may have been partly accomplished since Columbus's ships first plowed the waters of Colon Bay in October, 1502.

The Rio Grande River and its tributaries do not now enter Panama Bay except as overflow from the new Miraflores Lake. This lake acts as a settling tank and thus considerably reduces the sedimentation in the bay. Sedimentation in the Colon Bay is not now nearly so active as formerly, because much of the land around the bay is nearly worn to base level. On the other hand, the land is, very probably, still slowly rising, and if so the harbors and the approaches to both locks are still being slightly decreased in depth. The rise, if any,

must be so slow that a little dredging will easily take care of it. Then, again, the rise may stop or sinking may begin at any time. Tidal currents tend to fill in the channels at many places in the bays, but dredging easily keeps them clear, especially as the silt brought in is very fine.

GENERAL GEOLOGY OF THE CANAL ZONE IN ITS ENGINEERING RELATIONS.

GENERAL ENGINEERING RELATIONS.

Within the Canal Zone there are many different kinds of rock. Many of the rock units, however, occupy relatively small areas, so that any considerable excavation may pass through several of them. Most of the Canal Zone types can be included in 11 different groups of bedded and noncrystalline formations and 6 different groups of igneous or crystalline rocks. Each rock unit, however, may vary considerably from place to place, especially in such physical characteristics as shearing, jointing, texture, and hardness. They all differ somewhat in age, in character of material, and in origin. Figure 1 shows a general geologic section across the Isthmus, showing the different formations between the Atlantic and the Pacific shores. Figure 2 shows the rock succession in the Canal Zone.

All of the rock descriptions following have a bearing on the engineering work, especially on the excavation methods used in Culebra Cut. Each description is followed by a discussion of the practical considerations that particularly apply to that formation. However, the general phases of practical interest are summed up first.

The cost of breaking any rock for excavation depends on three chief factors, which are: (1) The hardness of the rock and its resistance to drilling; (2) the minimum size to which it must be broken to give greatest efficiency of results in handling; and (3) the tenacity or resistance to breakage of large masses of the material.

If the rock is hard the cost of drilling is increased not only by the longer time required but also by the larger cost of sharpening drills, greater drill breakage, more frequent delay from drill bits sticking and from broken drill points obstructing and sometimes necessitating the abandonment of the holes, and easier deflection of the drill hole if it crosses at an acute angle an open joint or fracture zone containing soft or crushed rock.

The degree of smallness to which the rock must be broken depends chiefly on the size that gives greatest economy in handling consistent with the capacity of the excavating machinery and the use, if any, to which the material is to be put. A steam shovel with a dipper of 4 or 5 cubic yards capacity can pick up, balance, and dump on a railway car a bowlder weighing several tons. The most economical

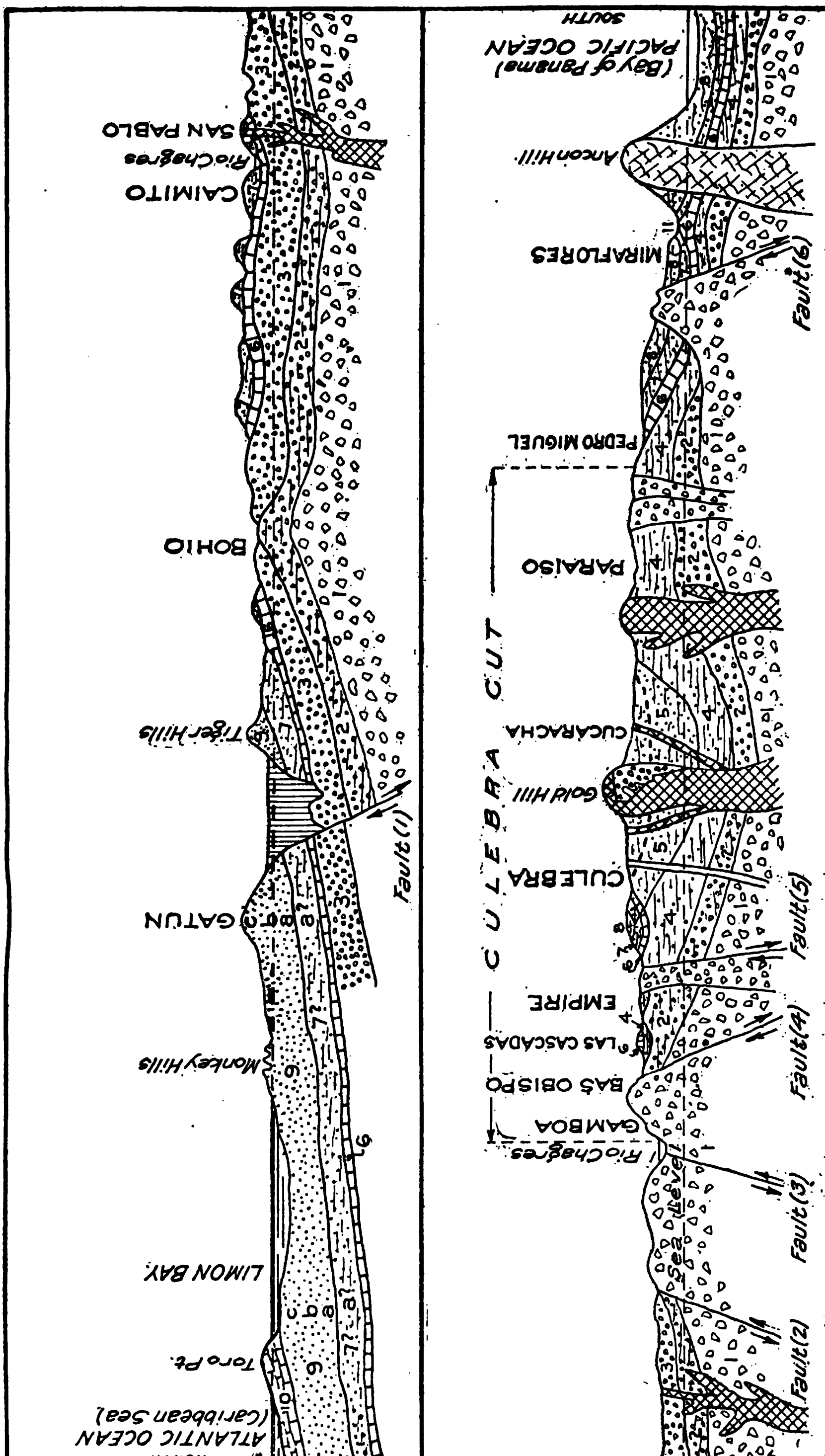


FIGURE 1.—Generalized geologic section across the Isthmus. Lower view shows continuation of upper view.

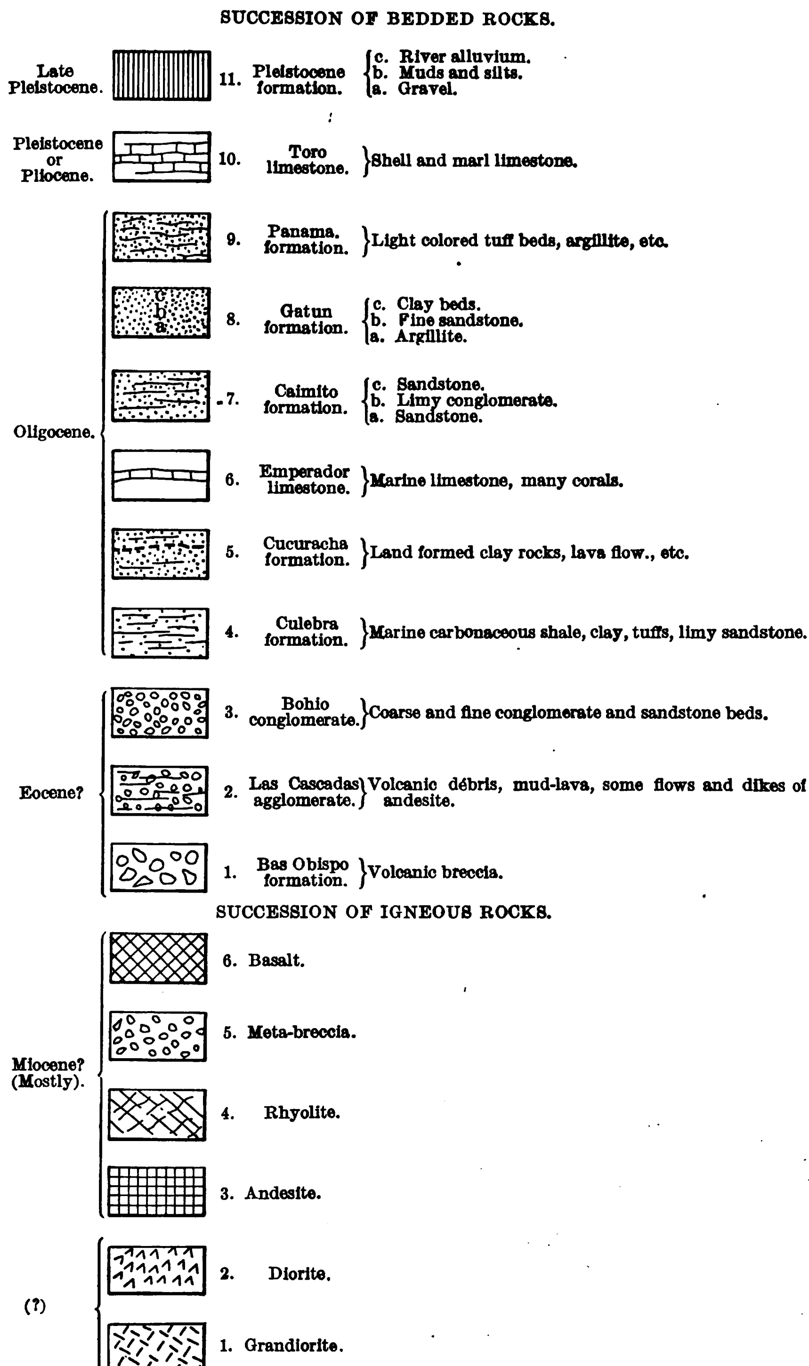


FIGURE 2.—Rock succession in the Canal Zone.

size to which the material should be broken ordinarily has to be determined by experiment.

The resistance of large masses of relatively hard rock depends not nearly so much on the tenacity of the solid rock as on the extent to which it is cut by natural joint, bedding, and shear planes. If it were desired to have the maximum size of the fragments not more, say, than 1 cubic yard, and if the joints happened to be well developed more or less at right angles to each other and so spaced that they divided the rock mass into fragments of not more than a cubic yard each, then the holes would not need to be so closely spaced and the charges could be much lighter to give the desired effect than if the joint planes were 2 or 3 yards apart or absent. If the material excavated is to be crushed and used for road making or concrete work, a high amount of jointing and fissuring lessens the amount of crushing necessary and greatly cheapens the cost of the product. On the other hand, if great coarse fragments are needed for armoring a breakwater against sea waves or an embankment against river currents, much jointing spoils any rock for such purposes, however suitable it may otherwise be. Soft argillaceous rocks with little tenacity are easily and cheaply drilled, and some such rocks on the Canal Zone were locally bored with augers. The holes in rock of this kind may be much farther apart and the explosive used may be a cheaper, lower grade and a slower acting one than would be required in hard rock.

ROCK FORMATIONS AND SPECIFIC ENGINEERING RELATIONS.

BAS OBISPO FORMATION.

The Bas Obispo formation is the oldest isthmian formation, so far as is known, and is probably of pre-Tertiary age. It was formed of rock fragments and ash blown from old volcanic vents. The débris settled over the surrounding region and was subsequently cemented into fairly hard rock by the slow-acting processes of rock cementation. Locally it shows some rough bedding and some rounded water-worn fragments. In composition it belongs to the group of rocks called andesites, and technically would be classed as an andesitic breccia. It outcrops extensively at Bas Obispo and near old Panama, and small outcrops rise above the alluvium near Miraflores and Diablo Ridge.

About 7,000 feet of the north end of Culebra Cut has been excavated in this formation. It is relatively hard and tenacious, except locally where it has been sheared by faulting. These locally faulted places have let down some masses and fragments of loose rock; but these were relatively unimportant as slides. On the whole, this

material has stood fairly well at steep angles and will continue to do so. In blasting it broke out in relatively large fragments and did not readily weather or wash; so the excavated material from this section of the cut was in greater demand for fills and dams, for which maximum stability was necessary, than the softer and more friable rock.

LAS CASCADAS AGGLOMERATE.

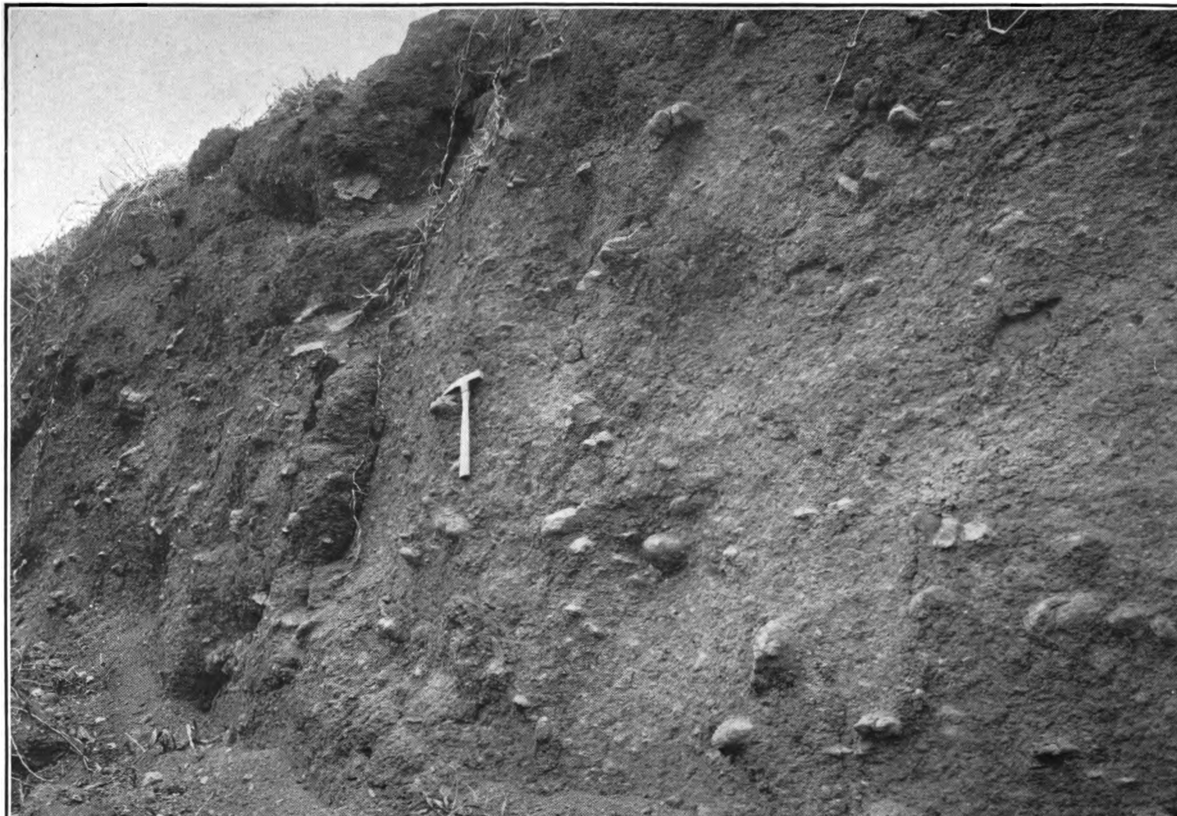
The Las Cascadas agglomerate also had its origin in fragmental rock material blown from volcanic vents and later washed down into different beds and masses. It rests uncomformably on the Bas Obispo formation, is much less consolidated and cemented than the latter, and is of much more recent origin. It is a greenish to gray, basic agglomerate, which contains large and small subangular fragments in a fine-grained groundmass of volcanic clay and tuff (Pl. V). The whole is arranged in massive to roughly bedded deposits, often unconformable with each other. Interbedded with these deposits are andesitic flow-breccias, some fine-grained grayish and some coarse-grained dark andesitic flows, and a few easily crumbled lava-mud flows which show columnar jointing where exposed in the canal (see Pl. XXVIII). The whole is cut by large and small basalt dikes. The formation outcrops extensively along the canal between Empire and Las Cascadas.

In degree of hardness and tenacity and in texture the rock of this formation presents great variety, but, on the whole, it is much softer and more friable and was cheaper to drill and blast than the Bas Obispo rock. Several considerable slides developed in it, due chiefly to local areas of weakness and faulting, and to its somewhat clayey character and ground-water content. These are described in detail under another heading. The extent and relative position of this formation is shown in figure 1.

BOHIO CONGLOMERATE.

The Bohio conglomerate consists of beds containing water-worn cobblestones and pebbles. These beds are separated from each other by layers of sandstone and clay rock. The lower part of the formation contains more cobbles and pebbles than the upper part and seems to be largely a product of running water. It is generally fairly well bedded, though locally massive, and contains hard bowlders, up to a few feet in diameter, of andesitic, dioritic, and other igneous rocks.

The upper part of this formation is of the same general composition as the lower part, but contains some beds of dark-gray clay marl rock which have the fossil remains of foraminifera—minute shell-bearing animals. The cobbles, bowlders, and gravel are from cherts, andesites, and diorites, and were derived from the older



LAS CASCADAS AGGLOMERATE. SHOWS CHARACTER OF VOLCANIC AGGLOMERATE MATERIAL EJECTED BY EXPLOSIVE OUTBURSTS FROM ANCIENT VOLCANOES THAT HAVE LONG SINCE CEASED TO EXIST.

intrusive masses of igneous rock now found at intervals along the central part of the Isthmus.

The formation must be at least 1,000 feet thick, and it outcrops extensively in the vicinity of Bohio and near Caimito Junction. Though not outcropping in the Culebra Cut, it was encountered in many of the cuts near Bohio on the new line of the Panama Railroad. It is somewhat difficult to drill, on account of the many hard cobbles and bowlders that it contains. Lack of jointing makes it rather more difficult to blast than might be expected from the fact that the matrix filling its interbowlder spaces is relatively soft and friable.

CULEBRA FORMATION.

The Culebra formation contains an upper and a lower member.

The lower member (fig. 1 and Pl. XV) consists of dark, well-laminated beds of soft shales, marls, and carbonaceous clays, with some pebbly, sandy, and tufaceous layers. There are a few thin beds of lignitic shale, but the whole upper part of the formation contains considerable organic matter. It outcrops in the Culebra Cut, near Culebra, and near Pedro Miguel.

The upper member consists of calcareous beds and lenses ranging in character from sandy limestone to calcareous sandstone, 3 to 10 feet thick, separated by partings of dark carbonaceous clays and fine-bedded tuffs (fig. 1 and Pls. VI and XV).

Locally this formation gives off a little natural gas and in some small areas it shows slightly bituminous shales.

The lower member of this formation, because of its soft, friable nature, could be drilled and blasted easily and was economically handled by the steam shovels. In spite of its weak and friable character it was relatively less given to sliding than, say, the Cucuracha formation, owing to the following facts:

(1) It is fairly well laminated or bedded, and the thin beds are relatively horizontal, except locally; hence there is practically no tendency toward sliding along the bedding planes.

(2) It is slightly sandy to granular and both its granularity and its bedding planes cause it to be better drained than the more clayey formation (the Cucuracha) in which maximum sliding developed.

(3) It seems to be relatively free from particles of chlorite and other greasy ferro-magnesian minerals which contribute greatly to the instability and mobility of the Cucuracha rocks.

The upper member of the formation contains many thin beds of sandy limestone and limy sandstone that are fairly resistant to drilling and blasting. They also strengthen the slopes and thus locally tend to prevent slides.

Certain local areas of the Culebra formation became heated, generally soon after having been exposed to the atmosphere by drilling

or blasting. This heating was due to the oxidation of finely divided pyrite. It thus was necessary in certain areas to test the drill holes to determine whether they had become hot and therefore dangerous to load with dynamite. This matter of heating ground is discussed more fully in a subsequent section. (page 71)

CUCURACHA FORMATION.

The Cucuracha formation (see figs. 1, 3, and 4 and Pl. XV) is here described in considerable detail, because in it not only the Cucuracha slide but also the big Culebra slides developed. It is so named because of being the site of the Cucuracha slide and because it is typically exposed near Cucuracha village.

The formation consists of a dark green, massive and locally bedded, slightly indurated, volcanic clay rock of andesitic composition. It is a land-deposited formation, overlying the marine Culebra beds, from which it is separated by 10 to 20 feet of slightly indurated gravel. It is the upper part of what Hill [a] and Howe [b] called the Culebra formation.

Locally it contains red beds and lenses, but these are of the same general character as the green clay rock in which they are interbedded, except that they contain slightly more iron and alumina and a little less silica. In certain beds there is a network of small irregular joints contiguous to which the greenish clay rock has turned red; such a change seems to be due to the oxidation of the greenish ferrous iron to the red ferric condition by surface waters. In some of these red beds, however, there has been some local concentration of iron and alumina products.

In addition to the red beds there are a few local beds and lenses of gravel and of sandy, dark gray, tufaceous material. This gravel, like the gravel at the base of the formation, is fairly fine, loosely cemented, and consists of the rounded fragments of indurated shales, cherts, and concretions from the lower part of this formation and from some of the older rocks.

There are also four distinct beds of lignitic shale, 1 to 5 feet thick. They are the fossilized remains of former swamps.

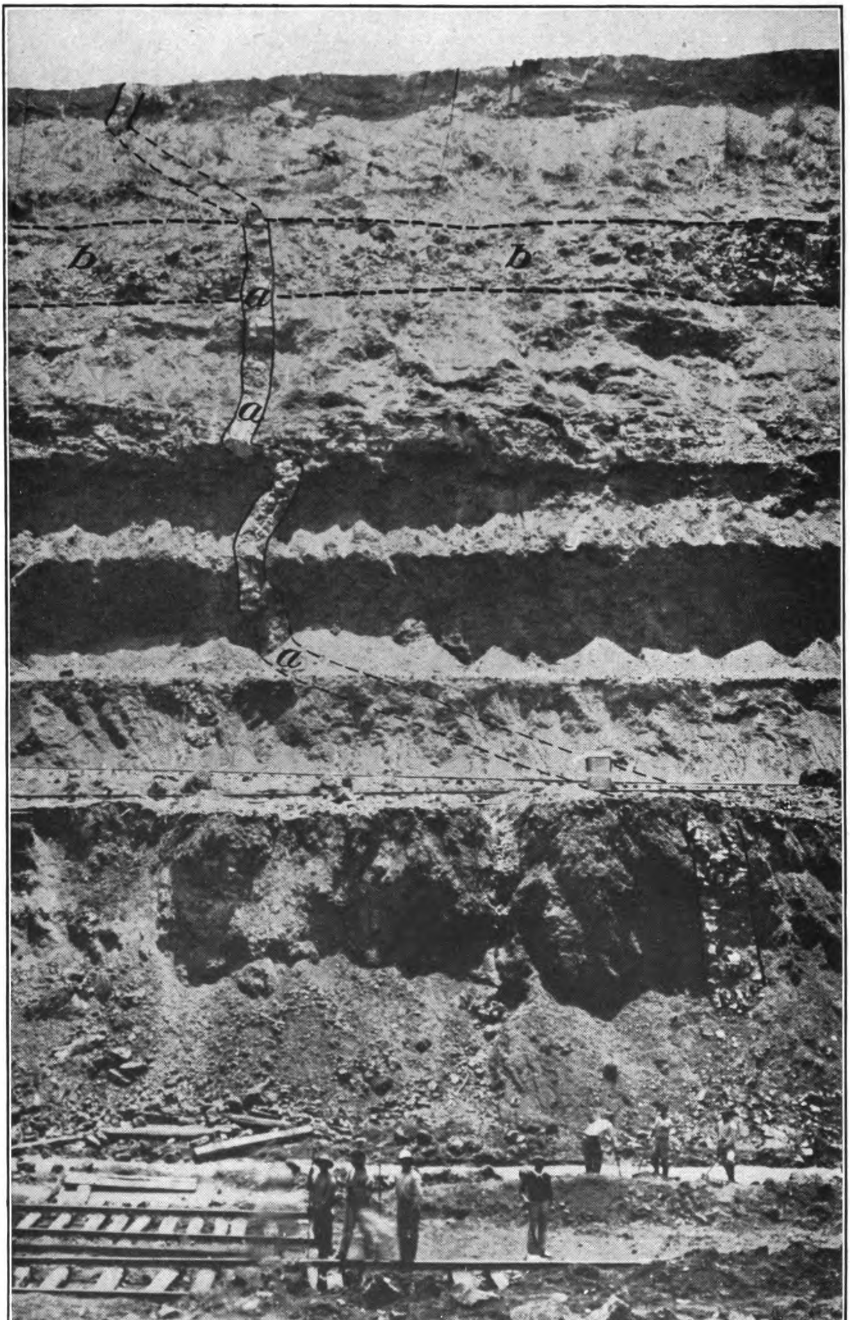
The formation is cut by some large and some small basaltic dikes (Pls. VII and XV), but these have caused scarcely any metamorphism. Faulting has considerably broken the beds and, owing to their soft and brittle character, relatively small faults, where the movement seems to have been less than 75 feet, have resulted in shear zones up to several feet wide. These rocks weather readily, and are

[a] Hill, R. T., Geological history of the Isthmus of Panama and portions of Costa Rica: Bull. Museum Comparative Zoology of Harvard College, vol. 28, 1898.

[b] Howe, Ernest, Canal Commission Ann. Report 1907, Appendix E, pp. 108–138; Isthmian geology of the Panama Canal: Econ. Geol., vol. 2, 1907, pp. 639–658; Geology of the Isthmus of Panama: Am. Jour. Sci., vol. 26, ser. 4, 1908, pp. 212–237.

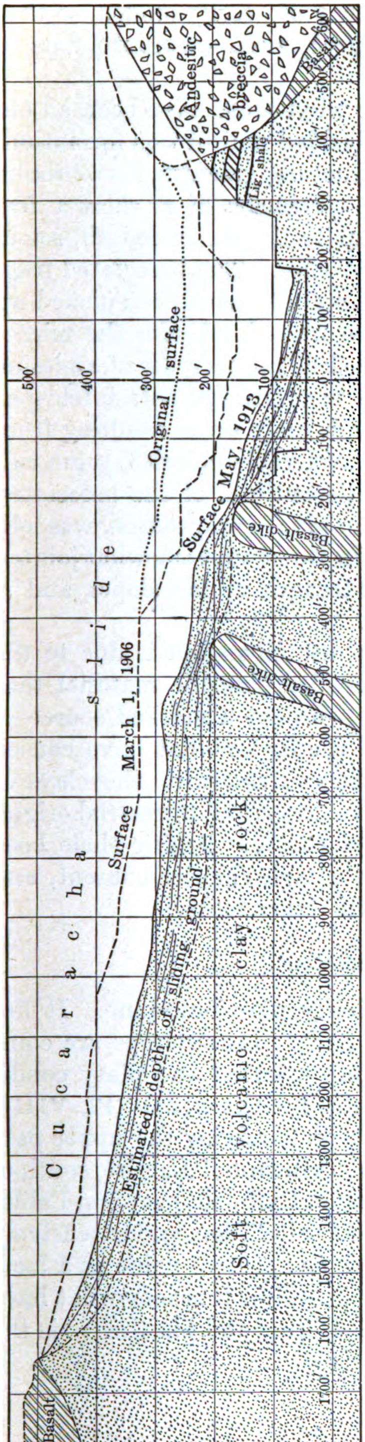
SECTION IN CULEBRA CUT, NEAR CULEBRA.

Bedding of upper part of Culebra formation; thin limy sandstone beds separated by partings of dark carbonaceous clay and shale. These beds contain the remains of oysters, corals, and other marine animals. The dip is southerly, toward Contractors Hill.



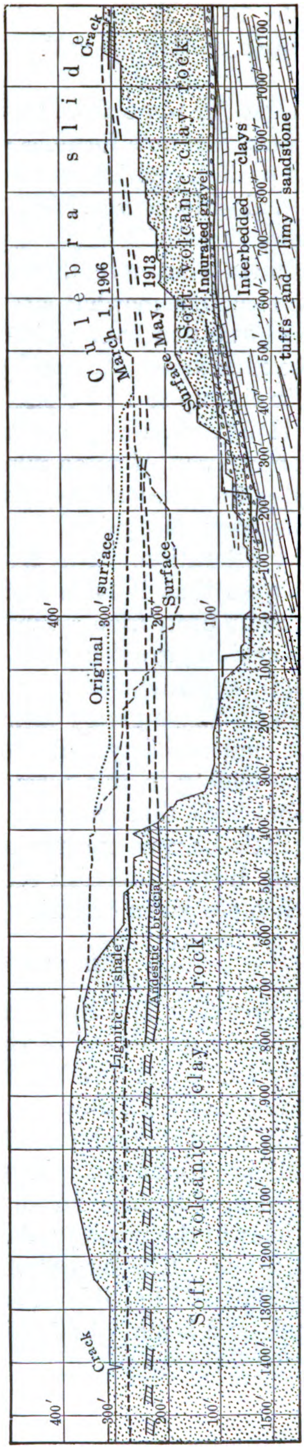
DIKES IN CUCURACHA FORMATION.

a, Faulted and sheared dike of basaltic rock that cuts the cucuracha formation in Culebra Cut, near Culebra. *b*, Old lava flow in cucuracha formation.



Station 1812, Elevation +50

FIGURE 3.—Cross section of Culebra Cut through Cucaracha slide.



Station 1782

FIGURE 4.—Cross section of Culebra Cut at station 1782. As shown on left, a large crack developed at the surface, due to the fact that the rocks have deformed the excavation. This figure and figure 3 illustrate at what flat angles these rocks will slide.

covered by 10 to 25 feet of red soil. They are easily eroded, so that the outcrops of this formation have mostly been worn into flats or valleys.

Extending for more than a mile over what must have been an old land surface, and now forming an interbedded unit of this formation, is a light to dark grayish, or, on fresh fracture, greenish, lava-breccia flow of andesitic composition. Hand specimens of it show a few little shiny faces of feldspar crystals up to 2 mm. in length, set in a groundmass that resembles indurated clay. The brecciated fragments are small, somewhat altered, and seem to have been picked up from the formation over which the flow moved. Under the microscope the rock is seen to consist of euhedral phenocrysts of andesine ranging in size up to 1 by 2 mm. and some crystals of potash feldspar set in a cloudy claylike groundmass, dark scaly areas resulting from the decomposition of some mineral, considerable chlorite, some calcite, and a little secondary quartz. The outlines of the brecciated fragments were recognized but their original composition was obscured by alteration. This altered andesite flow is somewhat jointed and weak, so that it adds but little strength to the slopes and is practically no protection against slides.

The prevailing grayish-green color of the formation is due to the fairly high percentage of very finely divided chloritic material that it contains. These greasy mineral particles are a marked source of weakness and mobility and are one of the factors that have caused maximum sliding in this formation. In contrast with the clays of the Culebra beds, these rocks are massive, largely of terrestrial origin, contain little organic matter outside of the few lignitic shale beds mentioned, have a greenish color from a high chlorite content, and are much more given to sliding than the other rocks.

EMPERADOR LIMESTONE.

The Emperador is a light-colored, fairly pure limestone. It lies unconformably on several of the older beds. Its outcrops are comparatively small and weather locally into a pitted and platy condition. Near Las Cascadas a section cut by the canal (Pl. VIII), shows the limestone, about 25 feet thick, overlying the upper part of the Culebra formation. It outcrops northwest of Empire, south of Las Cascadas, on the new line of the Panama Railroad, near San Pablo, near Frijoles, in the swamp southeast of Diablo Ridge, and extensively near Alhajuela. The formation also has prospective value as a local source of lime and possibly of cement. In places it is somewhat hard and tough, and is almost as resistant to drilling and blasting as is the Bas Obispo formation.

EMPERADOR LIMESTONE BEDS NEAR LAS CASCADAS, SHOWING FAULT.

a, Emperador limestone. It contains the remains of many sea animals, especially corals. *b*, Large fault which cuts off the beds here.

CAIMITO FORMATION.

The Caimito formation, which overlies the Emperador limestone, consists of three members, as follows: (*a*) A basal light-gray, soft, argillaceous, or claylike, sandstone, which grades upward into a yellowish argillitic sandstone that is bluish gray on fresh fracture; (*b*) a peculiarly calcareous conglomerate with some fragments of much decayed basic rock, which locally give a bright-green stain to small patches of the formation; (*c*) a light-colored to yellowish argillaceous sandstone fairly well bedded. The upper argillitic sandstone is the rock that outcrops in the Chagres River at Barbacoas, near San Pablo. Beds *a*, *b* and *c* may be seen in the section at Bald Hill, north of Miraflores. Bed *b* outcrops extensively at San Pablo and near the site of the proposed wireless telegraph station opposite San Pablo. The formation does not outcrop at all in the Culebra Cut. These rocks are relatively easy to drill and blast, and the weathered product from the more clayey beds of this formation might be suitable for the manufacture of common brick.

GATUN FORMATION.

The Gatun formation (figs. 1 and 2) consists of three members, as follows: (*a*) About 500+ feet of marls and argillites, or clay rocks, and some beds of soft sandstone and conglomerate; this member is bluish gray but locally contains many brown specks, indicating fragments of organic material; it is rich in the fossil shells of ancient marine life; (*b*) mostly fine, soft sandstone, about 100 feet thick, containing a few fossils; (*c*) light to creamy gray indurated clay beds.

The formation is extensive and constitutes the foundation on which the Gatun Locks are built. Fortunately, its fineness of grain renders it relatively impervious to ground water. The upper part of the formation weathers into red clay, and except where this is cut by streams, it covers the solid rock to a depth of 10 to 25 feet.

It is possible that the red clay, the weathered surface covering that obscures much of the Gatun formation, would be a good source of material for the manufacture of common brick. This rock has been used extensively for fills on the new line of the Panama Railroad, and in other places. It was convenient and cheap to excavate and load and answered well the uses to which it was put. However, it can not be used for fills that are subject to the scour of a river or of sea waves, because it abrades and weathers easily. This formation has much engineering significance because the Gatun Locks and Dam rest on it as a foundation. Its strength and adequacy to meet such foundational requirements are discussed under the heading "Foundations of the Gatun Dam and Locks" (p. 39).

PANAMA FORMATION.

The Panama formation is a light-colored well-bedded tuff somewhat acid in composition. Locally it contains some argillaceous beds. It outcrops extensively from Miraflores to Panama and in a few other places. The formation is at least 400 feet thick and overlies the Caimito beds. It seems to be relatively porous, fairly well bedded, somewhat jointed, and of a crumbly or friable nature. It was not difficult to drill or blast and is somewhat too soft for good road metal.

TORO LIMESTONE.

The Toro[a] limestone is sandy and fragmental, being locally a coquina or shell marl. Its type locality is at Toro Point, but similar appearing limestone fringes the Caribbean coast, except where large valleys have caused it to be eroded or covered with alluvium. In places it forms low bluffs or headlands, especially at Toro Point, west of the Gatun Dam, and at the mouth of the Chagres River. It is the rock from which Fort San Lorenzo was built. Rock from this formation was used as a hearting for the Toro Point Breakwater. It was suitable for such a purpose because of the ease and cheapness with which it was blasted and loaded onto railroad cars for transfer to the near-by breakwater. The soft and easily abraded character of this material prevented its use except as a core or heart. The breakwater had to be faced or armored with much harder and tougher rock, an abundance of which was available at Porto Bello.

PLEISTOCENE FORMATIONS.

The Pleistocene formations consist of (*a*) swamp deposits, black soil and silt, filling old channels to depths of 325 feet below the present sea level; (*b*) river gravels up to 10 feet above the present normal river levels; (*c*) old sea beaches 6 to 10 feet above the present beach level; and (*d*) bars, beaches, and the present river alluvium. All of these deposits have a distinct bearing on the engineering problems of the Isthmus. The deep swamp deposits not only made surveys difficult, but added much to the cost of building railroad fills across them. The river gravels were useful for ballasting the road, for local concrete work, and for other purposes. Some of the beaches yielded vast quantities of sand for making concrete. The present river alluvium locally has an agricultural value; and some of the river sediment, deposited as bars and shoals which partly obstructed the Atlantic and Pacific entrances to the canal, had to be dredged away.

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[a] Called Caribbean limestone by the author in reports of Isthmian Canal Commission for 1912 and 1913. See p. 63 and p. 570 of report for 1913.

IGNEOUS ROCKS.

The igneous rocks within the Canal Zone belong to six distinct groups or families as described below.

GRANODIORITE.

Granodiorite is a quartz-bearing, locally porphyritic rock, a member of the broad group of granitic rocks. It outcrops in a few places in the Chagres River Basin, for many pebbles of it may be found among the gravels of that river.

Another rock that may be classed as granodiorite but in reality is a dacite (or quartz-diorite-porphyry), is that forming Cocovi Island in Panama Bay. It was planned to use this rock in some of the smaller parts of the dry dock, hence it is here described in some detail. It is light colored, weathers almost white, and shows in the hand specimen only occasional shreds of dark ferromagnesian mineral. Under the microscope it is markedly porphyritic, with phenocrysts (large crystals in a finer groundmass) of andesine-labradorite greatly predominating over quartz, orthoclase, shredded and altered remnants of hornblende, and what probably was biotite. Many of the phenocrysts are cracked and broken and show zonal inclusions of glass. The largest are 6 mm. in diameter and from this size they range downward into fine groundmass crystals. The groundmass seems to be of about the same composition as the coarser crystals and shows a sort of pepper-and-salt effect. The accessory minerals are magnetite and apatite; also some secondary chlorite is present. The rock is strong, fine grained, and will make a good building stone.

DIORITE.

Diorite, a rock much like granite, but with little or no free quartz and with much dark hornblende, is found as rounded fragments among the gravel of the Chagres River, and in the Bohio conglomerate. Both diorite and granodiorite form some of the core masses of the mountains in the interior of Panama. The diorite is a tough well-crystallized rock and will serve well for building purposes.

ANDESITE.

Andesite, a rock of about the same chemical composition as diorite, is known at a few places in the Canal Zone. It differs from diorite in having reached the surface as a lava-magma, whereas diorite cooled below the surface and is therefore generally much more coarsely crystalline. Volcanic necks and dikes of andesitic rock cut the Las Cascadas agglomerate in various places. Similar dikes seem

to cut the diorite at Point Parfan, opposite Balboa. Rocks of this general character form the steep headlands at Porto Bello and constitute the material quarried and crushed there and transferred to Gatun for use in the concrete work of the locks. Huge pieces of this rock, from the Porto Bello quarry, were transported on lighters and used to armor the breakwater at Toro Point. It is a typical andesite, hard, strong, and dark colored. Shiny little crystal faces appear scattered over the surface of hand specimens of it. Under the microscope it shows many large crystals of andesine and andesine labradorite, together with large crystals of augite and some of hypersthene, all set in a fine-grained dark to brown groundmass. This groundmass contains minute crystals or microlites of essentially the same composition as the large crystals.

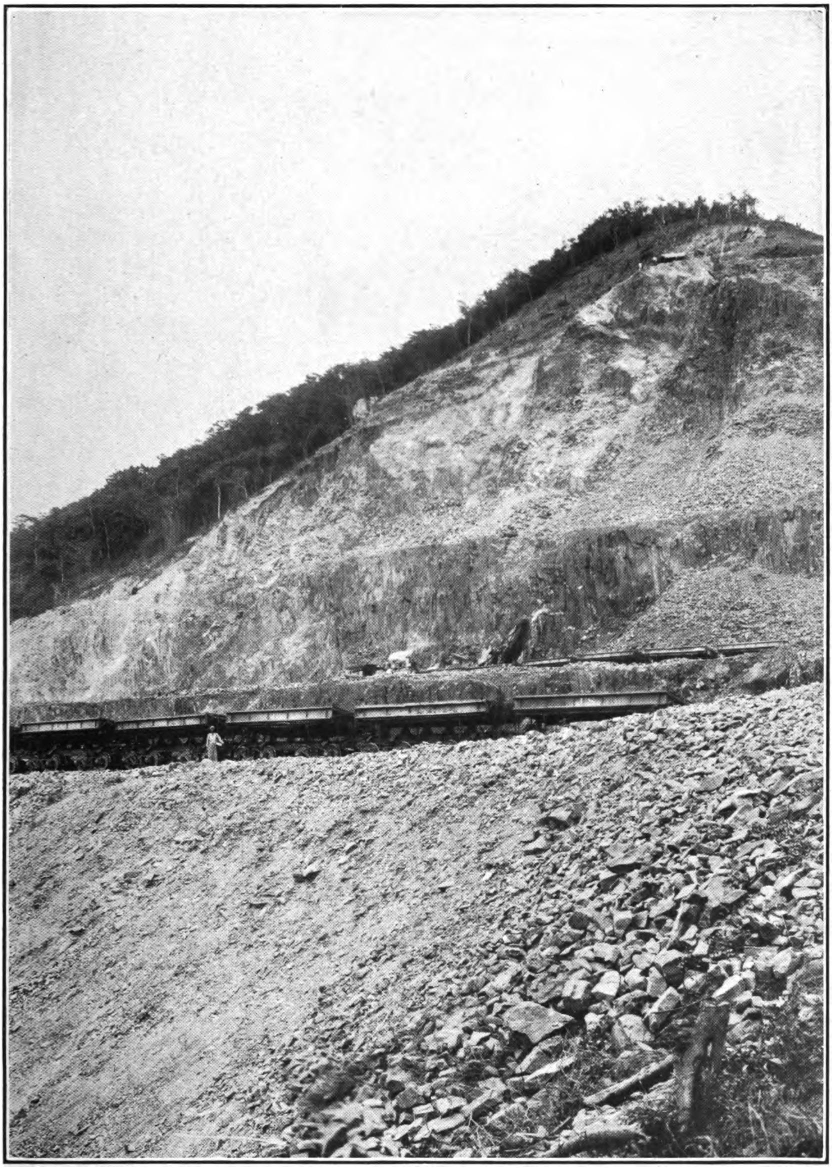
Rock obtained at Point Farfan, opposite Balboa, where the French had an old quarry, shows a groundmass relatively coarse for andesite. In fact, the large crystals or phenocrysts of andesine and augite are not much bigger than groundmass or small crystals in which they are set. Quartz is also present in this rock in irregular masses and in micropegmatitic intergrowths with feldspar. The rock is a quartz andesite in composition.

The well-crystallized character of both the Porto Bello and the Point Farfan rock renders them tough and resistant to abrasion by waves; hence they are well suited for breakwater or sea-wall construction.

RHYOLITE.

Rhyolite has the same chemical composition as granite, but is much finer in grain. Crushed rhyolite was used for the concrete work of the Miraflores and Pedro Miguel locks; therefore it is here somewhat fully described. It is the rock that forms Ancon Hill, and Culebra and Naos Islands, in Panama Bay. Ancon Hill is a slightly curved, roughly tabular intrusion, about half a mile long and several hundred feet thick, cutting the softer Panama formation of light-colored bedded tuff. It stands as a much elongated cone or short curved ridge, 654 feet above sea level and nearly 600 feet above the lowland that surrounds it (Pl. IX).

The rock is much fissured and jointed, so that it is easily crushed. It weathers to a light-buff color, but is bluish gray on fresh fracture. In the hand specimen it shows a fine texture with some small lathlike phenocrysts, the larger ones having faces about 1 by 5 mm. in size. Microscopically the rock shows some flow structure, especially around the phenocrysts, which are largely oligoclase or oligoclase-andesine, with a few small and considerably altered needles of hornblende. The phenocrysts are much in the minority and in size grade into the coarser particles of the groundmass. The groundmass is fine grained and slightly cloudy and decomposed. It consists largely of perthitic



ANCON QUARRY, ON THE SOUTHWEST END OF ANCON HILL.

aggregates of orthoclase and plagioclase, with some quartz and feldspar intergrowths. A small amount of free quartz is present. The chief accessory minerals are grains of magnetite scattered through the rock, some ilmenite, a little apatite, and some light-yellowish grains of secondary mineral showing locally in the groundmass.

This rock is strong, fairly tough, and on the whole is well suited for concrete work.

BASALT.

Basalt, a dark, basic, fine-grained lava rock, is rather plentiful on the Isthmus. As dikes it shows in Culebra Cut near Empire, Culebra (fig. 1 and Pls. VIII and XV), and Pedro Miguel. As more massive intrusions it forms Office Hill at Empire, the top part of Gold Hill; also hills near Paraiso, Pedro Miguel, Rio Grande, near the Panama Railroad track 2 miles north of Monte Lirio, and in many other places. In fact, most of the steep hills and ridges within the Canal Zone (Pls. I and II), except Ancon Hill, are formed of hard basaltic rock that formerly came up through the softer rock as dikes and cores of lava. The basalt near Culebra Cut contains practically no olivine, whereas that found in many other places is rich in that mineral.

This rock is hard and tough and has locally been used in building roads. If crushed, it would serve well for concrete work. Its use to armor the projected new east breakwater at Colon was proposed, but the rock is so cut with joints that it would not break in large enough pieces to resist the abrasion of sea waves. However, it was to be used as the first coat of armor over the softer and more easily abraded heart or core material, the whole to be faced with large blocks of the Porto Bello rock. Basalt was also used to a considerable extent for facing the water-level zone of the Gatun Dam. Because of its engineering importance it is described in some detail.

Gold Hill is capped by about 250 feet or more of basalt, and a curved basalt dike 75 to 100 feet thick forms the westerly and northerly periphery of the hill mass. The dike and the capping are fairly typical of the variety of basaltic rock occurring within the Canal Zone that does not bear olivine. Locally the basalt shows some columnar structure (Pl. X) and is considerably jointed. It is tough and strong and resistant to weathering, so that it generally forms hills and ridges which have only shallow coverings of soil. It cuts sedimentary beds of Oligocene age and was perhaps erupted in Miocene (?) time. It shows relatively little contact metamorphism.

Hand specimens of this rock show it to be dark, compact, fine grained, and even textured, and it is comparatively little weathered. Microscopically it shows fluxional or flow structure, markedly in specimens from the capping on the hill and to a much less extent in specimens from the dike. In the flow capping the feldspars are abundant, labradorite lathlike crystals, ranging up to 1.2 by 2 mm. in size, pre-

dominating. In the dike specimens the crystals are a little stouter and larger, and many of them are cracked and bent. Augite is fairly abundant and occurs mostly as pale grains and granular aggregates. The accessory minerals are small black specks and irregular aggregates of magnetite plentifully peppered through the mass, a little ilmenite, and some apatite. Epidote in light and dark yellow irregular patches is present as an alteration product from some of the feldspar crystals, for it fills the little cracks of those that are crushed and broken and occurs as cloudy masses and aggregates in the interior parts of others. Three thin sections were examined, but no olivine was noted in them.

Basaltic rock from a little hill near the railroad track and 1½ miles north of Monte Lirio was used to face the water-level zone of the Gatun Dam. This rock is somewhat coarser in texture than that just described, and its feldspars are more calcareous. Otherwise the rock is much like that of Gold Hill.

META-BRECCIA.

Under meta-breccia are classed the metamorphosed tuff, sandy and argillaceous beds, agglomerate, and breccia masses that form Gold Hill, Contractors Hill, Office Hill (Culebra), and the breccias at Pairaiso, at Empire, and at other places (see Pl. I, II, and XV). Around at least a part of the periphery of several of these masses, and projecting through each of them in one or in several places, are basalt dikes. All of these masses, so far as is known, are separated from the rocks surrounding them by a contact along which faulting has occurred. Both the Gold Hill and the Contractors Hill masses have been faulted downward some hundreds of feet (see Pls. XV, XIX, and XX), These meta-breccias are similar to certain phases of the Bas Obispo breccia. Disturbed bedding is found in their upper parts, so that a vertical section through them would look somewhat like a vertical section through the upper part of the Bas Obispo, and a part of the overlying Las Cascadas agglomerate, with some higher-bedded tuffs included. The evidence indicates that these meta-breccia masses were pushed upward as somewhat metamorphosed and toughened caps on top of basalt plugs or cores. On cooling, shrinkage and outlets for various dikes and apophyses caused a gradual settling back of these plugs to about their present condition. These breccia masses have acted as strengthening pillars to buttress some of the sliding areas in Culebra Cut. This function is discussed in a subsequent consideration of slides.

LAVA-MUD FLOWS.

In addition to the igneous rocks enumerated, there are several cooled and hardened mud-lava flows which are found in the Las Cascadas agglomerate. Many of these local masses show columnar structure (see Pl. XXVIII) and are rather hard, but on exposure to the air for a few years they crumble considerably.

BASALTIC COLUMNS EXPOSED IN CULEBRA CUT, NEAR CUCURACHA SLIDE, IN MARCH, 1913. CLOSE VIEW.

STABILITY OF THE ISTHMUS.

A brief reconnaissance of the geology of western Panama was made possible by a cooperative arrangement between the Isthmian Canal Commission, the Smithsonian Institution, and the United States Geological Survey. The information thus gathered, coupled with that obtained from a study of the Canal Zone geology, leads to the conclusion that the isthmian land first appeared as an archipelago of islands in a shallow sea. During the Oligocene period, when the Cucuracha formation was laid down, there seems to have been established, possibly for the first time, a land connection between the two continents. At least there is, as yet, no positive geologic evidence of an earlier connection. Before the close of the Oligocene, the sea again swept over the submerged land, leaving only a few islands above the surface of the water. It appears that the Miocene began with an emergence, and that until its close the isthmian barrier once more effectively separated the oceans. With the beginning of Pliocene time, the land again sank until only the highest points were left above the surface of the sea. Another uprise ushered in the Pleistocene, and before this period was well advanced the land stood several hundred feet higher than now. Again sinking began, and continued until the land was 6 to 30 feet below present sea level. The last uprise, according to the fresh appearance of the old raised sea beaches and other evidence, must have taken place within very recent time, probably within the last thousand years.

In all, there is a clear record of four oscillations and the beginning of another elevation. Hence the question: Is the canal in danger from this uprise? Should the emergence be rapid, of course it would be in some danger; but the fact is, that the average rate of uplift for say, the last 1,000 years has been something less than 0.03 foot a year, or less than 3 feet in 100 years. Dredging could, of course, take care of this rise with little additional expense above the ordinary dredging necessary for the annual upkeep of the canal. Then, too, there is always the chance that this motion will stop entirely, and a sinking begin. Arguing then from what has happened in recent geologic time, it may be concluded that the canal is not in any appreciable danger from the geologic instability of the isthmian land.

It is believed that the sinking of the ocean bottom outside the relatively shallow depths of the isthmian shore waters has been the chief cause of the earthquake periods that have, so far as the record go, visited the isthmus every 30 to 35 years, and that each of these seismic disturbances has resulted in some increased uprise of the land mass. This matter is more fully discussed under the subject of "Earthquakes." (page 74)

STRUCTURAL GEOLOGY IN RELATION TO ENGINEERING.

Under the subject of structural geology the folding, faulting, shearing, jointing, and some of the other changes that the rocks have undergone since they were formed is briefly discussed. All of these changes have some bearing on the engineering problems of the canal, but it is necessary to discuss many of them in connection with other topics treated under different headings, so only the main features and relations are here summarized.

FOLDING.

The bedded rocks were, of course, deposited in a relatively horizontal position. Since their deposition they have been folded and warped to various degrees.

From Gatun to the Caribbean the rocks of the Gatun formation dip gently northward and pass under the ocean at a slight inclination. The upper part of this formation is relatively fine grained and the lower part averages coarser. From such an arrangement of material, one would expect artesian conditions at Colon, especially now that Gatun Lake is almost 82 feet higher than that city. However, the rocks may be too fine grained and dense to permit flow of water through even their coarser lower beds. It is said that a well, some 600 feet or more deep, sunk by the Panama Government in Colon, furnishes considerable water, but develops no pressure at the surface.

A noticeable downfold or syncline in the bedded rocks crosses Culebra Cut in the vicinity of Gold and Contractors Hills. The axis of this trough trends almost northeast and southwest. Its greatest engineering significance is that it causes the stronger limy sandstones of the upper part of the Culebra formation to be bowed downward far below the bottom of the canal, so that they do not strengthen the slopes in the deepest part of Culebra Cut. The slopes where the worst slides have developed are composed only of the rocks of the Cucuracha formation, already described. The stronger limy beds lie below this formation, and outcrop as strengthening factors in the slopes of Culebra Cut on both sides of this downwarped trough or syncline, which is nearly 2 miles across.

There are many other minor flexures and small folds which have tilted the beds at angles up to 45° or more, but in general the bedded rocks are relatively flat and horizontal.

FAULTING AND SHEARING.

From the various oscillations of the land above and below sea level, as already noted, one would expect that the rocks constituting the isthmian land mass would have become broken and dislocated

in these upward and downward movements, and this has happened. Great fracture planes cut the rocks and trend mostly northeast-southwest, or approximately parallel with the axis of the land mass, with some minor fractures leading in other directions. Along these fracture planes differential movements, some of which measure hundreds of feet, have taken place. The frictional drag of these movements has crushed and broken the softer rocks for several feet on each side of the plane of motion.

This faulting has had a most important bearing on engineering, because the faulted zones, especially where the rocks are extensively crushed and broken, have tended to promote slides. The present faults date from Miocene time or later, and most of them are probably of Pleistocene age. At any rate, so far as the digging of Culebra Cut is concerned, these faults have increased the cost of the canal several millions of dollars. The relation of the faults and sheared zones to the slides is fully discussed elsewhere in this report. (page 48)

The chief faults trending across the canal are shown in figure 1 and Plates XV and XVI, but there are many more than those indicated there.

SUBMARINE ESCARPMENT AT PANAMA BAY.

Panama Bay is shallow out to its mouth. Beyond that the depth increases from 100 to over 1,000 fathoms in a short distance. This deepening is indicative of a great submarine fault escarpment passing just in front of Panama Bay. That there is an important fault escarpment there is established by the following facts:

On October 1, 1913, a considerable earthquake shocked Panama. It was especially severe in the southern part of Las Santos Province, where it seriously damaged several buildings. With the beginning of this earthquake the submarine cable from Panama City up the west coast broke. It parted just where it passes from the relatively shallow water of Panama Bay to the deep water beyond. When the break was located by the repair ship it was found that half a mile of one of the broken ends, which lay along near the foot of this submarine escarpment, was completely covered by débris and had to be abandoned and a new piece spliced in to take its place. It is, therefore, evident that the cable broke as the result of differential movement along this old fault plane, and that this movement caused the earthquake, and jarred down the submarine material that buried half a mile of the broken end.

About 1882 an earthquake shock, accompanied by the breaking of the cable, occurred in about the same way and at approximately the same place.

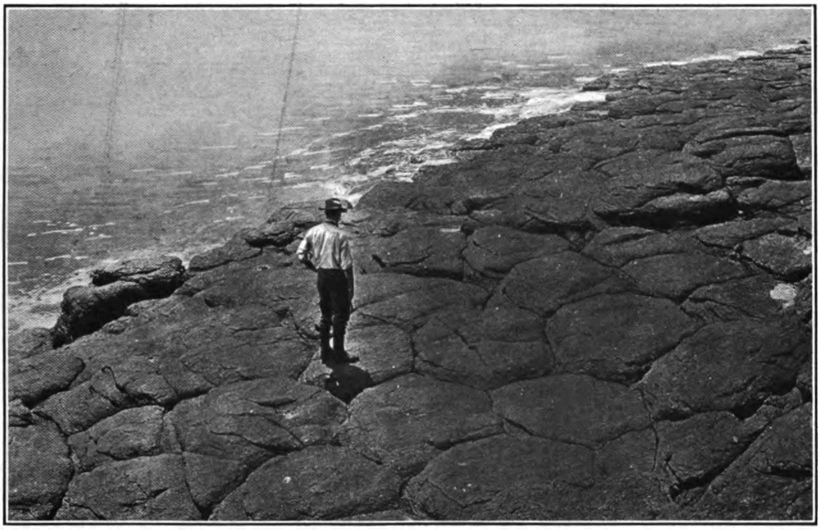
FISSURING AND JOINTING.

As mentioned previously, within the Canal Zone there are many dikes, cores, flows, and small masses of igneous rocks. These, while still in a molten condition, were projected upward through the bedded rocks. On cooling they were much cut by the developing of joints and shrinkage cracks, and later many of them were somewhat sheared by faulting.

The jointing and fissuring (Pl. XI) of these rock masses has had a direct bearing on engineering results. The great amount of jointing and fissuring in the Ancon Hill rhyolite cheapened considerably the cost of quarrying and crushing that rock for use in the concrete of the Pacific locks. On the other hand, one of the reasons why the Porto Bello rock was more expensive to use was because it had few joints and fissures, and hence broke in large masses that were expensive to load and to break into smaller pieces. The difference in jointing between these two rocks was due to the fact that the Ancon Hill rock is a relatively small, tabular-shaped mass which cooled quickly and developed many joints and shrinkage cracks. It was then not strong enough to resist the crushing effects of faulting, and subsequent movements of this kind still further sheared and crushed it. On the other hand, the Porto Bello rock mass was much larger and cooled much more slowly; consequently it developed relatively few shrinkage cracks and was little affected by faulting.

Certain dikes and lava flows that for a time held back the Cucuracha slide would probably have been strong enough to have prevented further sliding there but for the fact that they were cut by many cooling and shrinkage joints and fissures. These dikes were large and for a year or more they held back the sliding material. However, when the cut had been brought to final depth in front of them, the accumulated stresses of the material behind caused them to shear off at points where they had been greatly weakened by joint planes (Pl. X). This gave a renewed activity to the Cucuracha slide that brought down into the canal over 1,000,000 cubic yards of material.

It has already been pointed out how the excessive jointing in some large outcrops of basalt a few miles south of New Frijoles prevented the selection of this material as armor for the east breakwater. Several other basalt outcrops were, for a similar reason, also found unsuitable for such use. Because of minimum jointing, Porto Bello rock when blasted yielded a large proportion of fragments that weighed several tons; hence coarse "armor" rock for the west breakwater was taken from Porto Bello. It was thought that the coarser product of the jointed basalt south of New Frijoles would be used for the first covering over the softer heart material in the east breakwater. The coarse "armor" rock for this will, however, probably have to be taken from Porto Bello, or from Sosa Hill, Balboa.



A. COLUMNAR JOINTING OR SHRINKAGE CRACKS IN BASALT, MALONIS ISLAND, PANAMA BAY. NOTE LARGE SIZE OF THE COLUMNS.

B. HORIZONTAL JOINTING OR SHRINKAGE CRACKS IN BASALT, MALONIS ISLAND, PANAMA BAY. THE JOINTS GIVE THE APPEARANCE OF BEDDING.

(Photos by E. D. Christopherson.)

In the latter rock the cooling joints seem to be far enough apart to give massive fragments large and heavy enough for "armoring" a breakwater exposed to sea waves.

INTRUSIONS.

As already explained, many small and large masses of lava were forced into or through the bedded rocks. Many of these intrusions locally disturbed the attitude of the invaded rock beds, tilting them up at various angles. Occasionally contact with the hot lava baked and metamorphosed the disturbed beds, but most of the intrusions caused only slight change in the beds.

These intruded dikes and masses have locally acted as piers and buttresses to strengthen weak slopes against sliding. The most noteworthy of these strengthening intruded masses are Gold and Contractors Hills.

ROCK MATERIAL USED IN CANAL CONSTRUCTION.

In the constructional work of the canal much nonmetallic material of local origin was used. The relative cost of excavating, loading, and transporting such material to the places where it was to be used, as well as its physical properties and general suitability for different uses, were features to be considered in planning the location of the necessary rock quarries and gravel pits.

DIFFERENT TYPES OF ROCK MATERIAL USED.

In all, seven different types of rock material were used, as follows:

1. Hard, tough, crystalline igneous rock, broken so as to pass through a 3-inch or 4-inch round-hole screen. Vast quantities of this were used to mix with cement for the concrete work of the locks.

2. A considerable amount of fine screenings (inch mesh) were used for light concrete work, road work, locally for railway ballast, etc.

3. Great pieces of hard, tough, igneous rock, some weighing several tons, were used to armor the west breakwater, Colon Harbor, against the destructive effects of ocean waves.

4. Filling material of all kinds, mostly soft rock dug out of Culebra Cut, was used to fill in swamps, build up "made land" where necessary, to form a large part of Gatun Dam and for the heart or core of breakwaters.

5. Soft mud dredged out of canal channels or from borrow pits was pumped into certain swamp areas to fill them and to fill the spaces between the coarse fragments of Gatun Dam, thus creating a seal to insure water-tightness.

6. Clean sand, free from organic matter, was used for concrete and other construction.

7. Gravel was used for railway ballast and locally for concrete and for other purposes.

SOURCES OF MATERIAL.

ANCON HILL.

Nature supplied the Canal Zone with some excellent sources from which to obtain rock for concrete work. The best of these is Ancon Hill, which furnished the crushed rock for the Miraflores and Pedro Miguel Locks. It consists of a tabular mass of rhyolite nearly half a mile long and some hundreds of feet thick (fig. 1, and Pl. IX). The rock is rather hard, so that it resisted erosion or wearing down by the streams that cut away the softer rocks around it. Because of this hardness Ancon Hill stands over 600 feet above the low lands that nearly surround it. The rock in this hill is much jointed and broken and is easily blasted; relatively little further crushing by machinery is necessary to prepare it for use in concrete or road construction.

In this instance the faulting or breaking of earth blocks in past ages has directly aided construction by cheapening the cost of crushed rock for the concrete work of the Pacific Locks. The same period of faulting, however, has been a hindrance in the excavation of Culebra Cut, for it locally weakened the rocks there and gave them a greatly increased tendency to slide. A detailed description of this rock is given on page 28.

PORTO BELLO QUARRY.

The Porto Bello quarry and crushing plant, located in Porto Bello Harbor, about 20 miles northeast of Colon, furnished the crushed rock for the Gatun Locks. This quarry is on a large area of andesitic rock which had few shrinkage joints and was too large and solid to be much broken by faulting. The joints are fairly well developed, but far apart, so that the rock breaks into coarse pieces when blasted. Each blast loosened a great deal of rock, but a large percentage of it broke along the joint planes into big blocks weighing several tons each. Many of these had to be broken by "adobe" blasting or "bulldozing" before they could be loaded and crushed, thus adding much to the blasting and loading costs. Here nature rendered little assistance in crushing the rock and rendering it more cheaply available for lock building, as it had done in the case of the Ancon Hill rock. Had the Porto Bello rock been well jointed, the United States would have profited to the extent of many thousands or perhaps millions of dollars. This quarry, however, did good service in furnishing large bowlders, which were used to face the west breakwater at Colon Harbor.

UNSATISFACTORY HARD-ROCK DEPOSITS.

In June, 1913, the Isthmian Canal Commission wished to find a hard-rock quarry that should be as convenient as possible to Colon and to the new line of the Panama Railroad. Most of the rock areas

on the Canal Zone stand up as ridges or hills. One of these ridges, 2 miles south of New Frijoles, was "spotted" from a railroad train. Then trails were cut to it and a few small strippings made. The rock proved to be basalt, but subsequent work showed that, like nearly all the basalt masses of the Canal Zone, it was much jointed and broke into fairly small fragments on blasting. This quality though very desirable in rock to be used for concrete or road work rendered the basalt at this place unsuitable for facing a breakwater—the chief purpose for which it was required—unless reinforced by large heavy bowlders. Several other hard-rock areas were examined, but were all found to be more or less sheared and jointed, so that they would break into pieces too small to be really suitable for warding off the attacks of sea waves.

SOSA HILL.

Sosa Hill, close to the Pacific entrance, was found to be a fairly solid mass of andesitic rock, which had few shear joints and in which the shrinkage joints were far enough apart so that it would largely blast out in pieces weighing some tons with a relatively small percentage of fine material. This then is the best source known within the Canal Zone of material for armoring against heavy sea waves. However, the andesitic rock from Porto Bello may break out larger and be more economical for this purpose than the product from Sosa Hill.

CHAGRES RIVER GRAVEL.

The gravel for railway ballast and other purposes was obtained from the Chagres River near Gamboa Bridge. This is practically the only source of gravel within the Canal Zone. The lower Chagres contains too much alluvium, and in the upper part most of the rocks are too hard and tough and the streams too weak, except in flood time, to furnish much gravel. The available deposits lie between the rocky upper and the alluvial lower parts of the river near the railroad bridge, and thus convenient to transportation. The Chagres deposit furnished most of the ballast for the new line of the Panama Railroad.

UNSATISFACTORY GRAVEL IN CANAL ZONE STREAMS.

The Canal Zone streams as a rule do not yield much good gravel for the following reasons: (1) They are too short and most of them rise in ridges of hard rock, which affords relatively little material that they can easily wear into rounded gravel; (2) except in the flood season most of the streams are too feeble to roll stones along and grind them into rounded gravel; (3) in the wet season, after heavy rains, the streams become raging torrents, which tend to sweep away into the Chagres River or into the ocean material that might otherwise be a source of gravel;

(4) much of the rock traversed by isthmian streams is soft volcanic tuff and agglomerate that is easily converted into fine sediment. This forms a large proportion of the material carried by the streams during flood time, and in the lower rivers it covers and obscures much of the gravel that might otherwise be available.

STABILITY OF CANAL FOUNDATIONS.

GEOLOGIC STRUCTURE OF FOUNDATION ROCKS.

GENERAL CONSIDERATIONS.

Geologic conditions surrounding the foundations of heavy structures largely determine the plan, cost, and efficiency of such foundations. For instance, if a dam is built on a foundation rock of limestone leakage may occur, and that leakage if not remedied is likely to increase, because limestone is slightly soluble in ground water. If the water comes from a surface where there is much decaying vegetation, its solvent power is greatly increased by the increased content of organic acids and carbon dioxide. Wherever such water can penetrate a crevice in limestone, it will slowly enlarge that crevice by solution. Consequently, most large caves occur in limestone. The limestone formations on the Canal Zone locally contain many caves, openings, and irregular pitted surfaces, because the decay of the luxuriant vegetation there gives the ground water a relatively high content of organic acids and greatly increases its power as a solvent. Hence considerable care is necessary in locating a dam on a limestone foundation rock in order to be sure that no leaks, which may later enlarge, will occur.

If a masonry dam is to be secured to the foundation rock along its bottom and at both ends, certain geological factors must be considered. If the rock is shaly, thin bedded, and cut by many joints or fault planes, there is danger that certain blocks or sections of rock, or the upper beds to which the dam is secured, may under great pressure slip on the rocks below them and cause the dam to give away. Along many fault planes and along some bedding planes there are smoothened partings that readily lend themselves to slipping. Furthermore there is not only the pressure of the water against the wall of the dam, tending to push it over, and thus straining to widen the fissures in the foundation rock to which the dam is secured, but there is also the hydrostatic pressure of the water tending to force itself into those fissures and bedding planes and thus to exert a lifting or floating strain on the dam and on the slabs of rock to which the dam is attached.

Another important item relating to dams is to see that excessive leakage does not occur either through the dam, around the foundatons, or through the rim of the dammed-in basin. In order to ascertain what the percentage of leakage will be, individual tests must be

made. The procedure should be about as follows: (1) An accurate topographic map of the region to be examined should be made; (2) the geology of the region should be carefully plotted on the topographic map and on sections, not only from surface indications, but from borings as well, the number of the borings depending on the requirements, the surface conditions, etc.; (3) the bore holes and any test pits that may be sunk should be plotted on the geologic map and all data as to elevation of the ground water in the different holes, flow of water from holes, depth at which water is encountered, character of material passed through, character of jointing and fissuring, slope and thickness of all the beds, hardness of material, etc., should be carefully recorded; (4) the fineness or coarseness of grain of the material and the proportion of each for all the geologic units should be carefully determined by experiment; (5) the permeability and absorptiveness of the different kinds of material should be carefully tested.

For very heavy structures it may be necessary to take care that none of the foundation piers or sills are set on a faulted or crushed zone in the rocks or on any locally soft area that would settle faster than would the other parts of the foundation. It is also necessary to be sure that the nature of the foundation rock is such that it will not be subject to slow swellings, deformations, or sliding movements toward contiguous excavations or valleys or toward caves or underground openings.

It might be well to mention here another rather remote contingency. In planning permanent structures of great cost, such as great churches or other delicately adjusted buildings or monuments, effort should be made to avoid building them across any major fault plane showing evidence of considerable differential movement in recent geologic time. A differential movement of only a few inches along a fault plane might almost wreck a building, even though the motion were slow enough not to produce an earthquake.

FOUNDATIONS OF THE GATUN DAM AND LOCKS.

POSITION OF GATUN LAKE.

The northern rim of the Gatun Lake Basin is formed by the Quebrancha Hills, which are a few hundred feet above sea level and trend northeast-southwest in a well-defined ridge. The seaward or northern slope of these hills is relatively gentle. Their southern or Gatun Lake Basin slope is much steeper and is a relatively straight line, except where modified by stream erosion. They seem to be monoclinal and give strong physiographic evidence that their southern escarpment is the locus of a large fault. Unfortunately, because of lack of outcrops, no definite stratigraphic

evidence could be obtained on this point. At any rate no part of Gatun Dam and no part of the locks is built across this probable fault zone, so that the locks would not be harmed in any way should fresh differential movement or faulting occur along it. A glance at the map comprising Plate IV will show how the whole drainage of the Gatun Basin, including the Chagres, the Trinidad, and the Gatun Rivers, joined forces and emptied out into the Caribbean through a gap in the Quebrancha Hills little more than a mile wide. In order to form Gatun Lake, therefore, it was necessary only to close this gap; but to do this was a huge task; it meant the building of the Gatun Dam.

THREE GREAT QUESTIONS INVOLVED IN DAM.

With the project of this great dam, three questions in geologic engineering presented themselves. They were: (1) As Gatun Lake would have an area of about 165 square miles and would be 85 feet above sea level and separated from the Caribbean by only a few miles, would the seaward rim of this lake be found to be porous, or composed of limestone and thus result in leakage? (2) Would the bedrock be adequate in strength and in water-tightness to meet the foundational requirements of the locks and dams? (3) What would be the best type of dam to build under the engineering and geologic conditions involved?

Regarding the first of these questions the following was found to be true. The oceanward rim of Gatun Basin was found to be in general a fine-grained argillaceous rock. It has already been described as the Gatun formation (p. 25). This rock is so fine grained as to be relatively impervious. It contains a few local lenses of gravel and conglomerate, but these seem to be discontinuous and therefore relatively harmless in the matter of allowing leakage. Fortunately, the limestone locally forming the upper part of the rim is not known to extend below the 85-foot, or lake, level in any important place. If it did, a troublesome leakage that might rob the lake of considerable water might develop in it.

The second question was also answered in the affirmative, for it was found that the Gatun rocks are relatively solid and compact and suitable for foundations of heavy structures. However, some writers, even recently, have affirmed that the Gatun rocks would soften into mud when Gatun Lake filled, and thus the locks and dam would sink their foundations and be damaged or destroyed. Opinions of this sort spring from a vivid imagination and not from facts. In the first place, the Canal Zone rocks for centuries have been saturated with all the water they can hold; nine months in the year the rains are so heavy that the percentage of absorption as compared with the

run-off is small; the rocks during that time carry all the water they can possibly contain. Secondly, just how the water is going to separate and break apart the minute particles of a fine-grained rock which are cemented together, without deforming movements to grind and disintegrate the rock, is difficult to understand. The Gatun rock might possibly become soft through deforming movement and mixing with water, but such movements are impossible where there is no lateral force, but only a downward or compressional load from the weight of the dam. This weight will tend to keep the rock in the same solid condition in which it originally was and is now. Solution had a chance to complete its effects centuries before the dam was built. If the weight of Gatun Lake is going to force water into the Gatun formation and cause it to soften into a semimud that will allow the dam to sink, then all the islands in Gatun Lake and all the hills around it, which are of the same formation, should also have their bases softened in the same way, and sink into the depths. Reports that the Gatun dam and locks are in any danger from sinking have not the slightest foundation on geologic data.

The third question, as to the best type of dam to adopt, was answered by the application of a few simple engineering and geologic principles. It was recognized that the cheapest dam would be one of earth and rock. Therefore, instead of dumping the trainloads of material brought from Culebra Cut and nearer excavations on some spoil bank, they were dumped on the Gatun Dam. In other words, this dam site was made a great dumping ground where many trains could run out and have their loads plowed off by machine unloaders. It was evident that if the base was made broad enough the dam would be amply strong to resist any water pressure that might develop, and would be nearly as secure as a ridge of hills. Also, an adequately wide base would provide a satisfactory foundation for the dam. In the matter of water-tightness, two main facts were evident: If the dam was high enough it would sink into any local areas of soft and spongy rock or soil that might be under it, and thus prevent leakage around its base; and if very fine material could be calked in so as to fill the interstices between the coarser fragments, the dam would be practically water-tight. It was to be nearly half a mile wide at its base and about 105 feet high, so it had ample base area for its elevation to make the foundation secure and to resist the head of water that Gatun Lake was expected to develop. In order to get the interstices between the coarser fragments filled with fine clay so as to make the dam water-tight, the outside rims of it were built of coarse material (fig. 5). Then suction dredges, operating in the river channels and flats on either side of the dam, pumped mud into the basin thus formed. This drained into the openings between the larger frag-

ments and formed a thoroughly compact center mass or core which is practically water-tight. Later this puddled core was covered with coarse material as a sort of facing and the water-line area of the dam was faced with hard basalt fragments. In this general way a spoil dam with a water-tight clay-puddled heart was built.

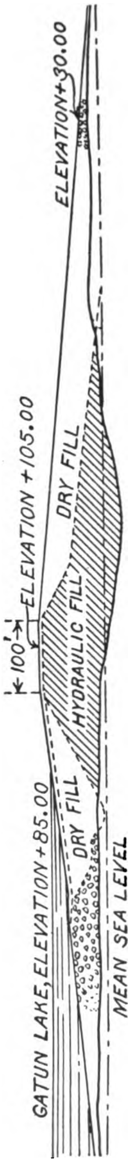


FIGURE 5.—Cross section of Gatun Dam showing dry fill and hydraulic fill.

DIFFICULTIES WITH HYDRAULIC FILLING MATERIAL.

The great magnitude of this dam may be realized by remembering that it is over 7,900 feet long, about 2,000 feet wide at the base, and 105 feet high. Figure 5 shows a cross section of it and gives some idea of its composition and plan. One of the construction difficulties was the excessive quantity of clay in the hydraulic filling material. This retarded drainage, and at times gave some difficulty in covering the puddled-in core with the dry-fill facing. The drainage of the core material was assisted by 20-inch drain pipes to remove the surface water and the very thin mud from the hydraulic-fill "pond" or sump. By varying the depth of this "pond" a greater or lesser amount of clayey material could be drained off. As the work progressed, the great mass of the dam slowly settled and became consolidated, and now seems to be almost as stable as a natural ridge or hill.

SOME DETAILS OF LOCK CONSTRUCTION.

The locks proper are founded on the bedrock of the Gatun formation, but the guide wall that extends out into Gatun Lake had to be built on an artificial foundation, because the bedrock is here about 150 feet below sea level. This wall is cellular and is built of reinforced concrete. The natural ground underlying it was about 8 feet above sea level. On this a wide fill with flat slope was made up to an elevation of 35 feet. Through this fill piles about 60 feet long and spaced 4 feet apart from center to center were driven and their heads were inclosed in a heavy reinforced concrete slab. On this the wall was constructed. As the work progressed a slow settling took place; however, the completed wall is now practically stable.

For the construction of the north guide and flare walls, foundational excavations to depths of about 70 feet below sea level had to be made before bedrock was reached. The material removed was too soft to permit loading with steam shovels and so was excavated

by suction dredges, which cut their way in from the old French canal. When the excavation had been completed the dredges were taken out, the channel they had made was dammed, the water pumped out of the excavation, and the foundations laid.

Although the foundation rock of the Gatun formation is relatively impervious to the movements of ground water, still it does not absolutely prevent seepage. Therefore, in order to prevent excessive hydrostatic pressure from Gatun Lake on the bottom floor of the lock chambers, the flooring of the upper lock was made strong enough to resist full lake pressure. Behind the remaining lengths of lock walls drainage was provided.

The details of how experimental dams built of the material to be used in the completed dam were made and tested, also of the manner of building the Gatun Dam, may be found in the annual reports of the Isthmian Canal Commission, particularly the report for 1908.

DESCRIPTION OF GATUN-LOCK FOUNDATIONS.

Concerning the character of the lock foundations at Gatun, Howe [a] writes as follows:

> Excavation for the locks will be almost entirely in the fine-grained argillaceous sandstone except at the lowest point to be reached at the extreme southern end, where conglomerate occurs beneath the sandstones. The rocks as a whole are well consolidated and make excellent cores with the diamond drill. When taken out and exposed on the surface they remain firm and hard; in rare instances they have been found to crumble and break down into a sandy clay. The rocks are well compacted and capable of supporting heavy loads when confined, but being poorly cemented are unable to withstand erosion and should be fully protected where such action is anticipated.
>
> On account of the very considerable amount of clay present in all of the rocks it is believed that they will prove to be almost entirely impervious to water. An exception will be found in the conglomerate referred to. Although this rock contains considerable clay, it has been found where exposed at about sea level in test pit No. 1 to be water bearing. On April 1, 1907, a pump discharging about 12 gallons per minute was just able to hold the water at an approximately constant level in the pit. The surface of the conglomerate exposed in the sides and bottom of the pit was about 240 square feet. Wherever this conglomerate is encountered, it may be expected to be water bearing at all times. In the test pit this rock stands in vertical walls without timbering and as long as confined will support heavy loads.
>
> In order to obtain some idea of the compression that might take place under loads equal to or greater than those due to the weight of the lock walls, a freshly exposed surface of the argillaceous sandstone near test pit No. 1 was leveled and smoothed by means of a file. Upon a square foot of this surface 100 steel rails, representing a weight of 77,350 pounds, were balanced upon the side of a short I beam, to the underside of which a casting, having a smooth surface 1 square foot in area, was firmly bolted. After a load of 37,128 pounds has been applied a settling of 0.011 foot was recorded, measurement being made by means of a Y level with reference to a previously determined bench. From this point on, until 48 hours after the full load had been applied, no further compression was noted. It is probable that the set-

[a] Howe, Ernest, Ann. Rept. Isthmian Canal Commission, 1908, pp. 124–129.

tling at 37,128 pounds was due to the pressing out of small inequalities on the prepared surface and that no measurable compression of the rock mass took place. The load applied to the square foot was equal to 537 pounds to the square inch, more than double the greatest pressure likely to be brought to bear upon the sandstones by the lock walls.

Further tests were made upon small pieces of rock taken from different test pits. None of these pieces was larger than one-eighth of a cubic foot. They were embedded in sand and the pressure applied to smooth surfaces one-half square inch in area. Seven tests were made upon pieces of conglomerate taken from the bottom of test pit No. 1. Some of this material had been exposed on the dump for 20 days. The samples failed at pressures of from 250 to 1,625 pounds per square inch; the mean of all the tests was 867 pounds to the square inch. Nine tests were made of the argillaceous sandstone taken from different test pits at the lock site and the site for the temporary spillway. Some of this material was taken from the walls of the test pits; other pieces had been lying on the dumps for a number of days. The samples failed at from 830 to 2,800 pounds per square inch. Two samples, both of which had been exposed on the dump for several days, showed no signs of failing when under pressures of 6,000 pounds to the square inch. Considering these as having failed at 6,000 pounds, the mean crushing load for the nine tests was 2,572 pounds per square inch.

INFLUENCE OF THE OLD CHAGRES RIVER CHANNEL.

As already explained, the Isthmian land during, say, middle Pleistocene time emerged until it reached an elevation of at least 375 feet above present sea level. As the land went up the stream currents were increased so that the streams cut deep narrow gorges for themselves. In this way the Chagres River intrenched itself some 325 feet below present sea level. After the emergence reached completion a slow sinking began and the streams, because of diminished velocity, began to fill their channels with silt. In this way the old Pleistocene channel of the Chagres was filled so that its presence was revealed only by borings made across the Chagres Valley at Gatun and at Bohio, where dam and lock sites were being explored. As to the character of the material which now fills the old channel or Pleistocene valley of the Chagres, Howe [a] says:

When the Chagres had succeeded in cutting something more than 300 feet below this level, the land began to sink slowly and the gorges were gradually filled with gravels, sand, silt, and clay. At different horizons in these alluvial deposits are shells and trunks and branches of trees that indicate a gradual rather than a sudden subsidence. * * *

* * * If subsidence takes place before the period of canyon cutting has ceased, as in the case of the Chagres, the velocity of streams is checked and they are capable of carrying fine material only, which is deposited far back from the mouths. In other words, one should expect to find at the bottom of such a gorge as the Chagres at Gatun a comparatively thin deposit of coarse gravel, sand, and a few bowlders, while the greater part of the alluvium should be of the finest clay and silt with a certain amount of fine gravel and sand mixed with it. Such, in fact, is the character of the alluvium filling the gorge of the Chagres, as shown by numerous borings made at Gatun. The boring records indicate considerable sand and gravel at points comparatively near the present surface; it is unlikely, however, that any sand or gravel,

[a] Howe, Ernest, op. cit., p. 127.

unmixed with clay, occurs in the deposits except at or very near the bottom. The reason for the boring records specifying "sand and gravel" as they do, is that when samples are taken from time to time during the process of sinking the hole, only the coarsest material is collected, the finer clay being held in suspension and carried off with the water flowing from the hole. In certain of the holes temporary flows of water were encountered, but after a few hours the flow invariably ceased. Such flows are believed to occur when, in the course of making a boring, the casing is introduced into a lenticular deposit of sand or water-bearing gravel under pressure from the overlying beds. The sands, being surrounded by much less pervious material, are in the nature of reservoirs in which water is stored under pressure, and when this pressure is released at the point where the casing enters the sands water may rise to the surface, if under sufficient pressure, and flow from the top of the casing until the pressures are readjusted. Far from indicating porous materials underlying the site for the dam, the occurrence of such flows of water only proves the extremely impervious character of the materials lying between the surface and the water-bearing beds.

As a foundation for an earth dam, the geological facts show that the alluvium filling the Pleistocene valley of the Chagres at Gatun will be entirely satisfactory.

The rock in which excavation must be made for the locks is firm and hard, and only slightly permeable to water; it will stand in vertical walls without timbering and will support loads many times greater than those to which it will be subjected.

Spillway sites 1 and 2 in the Trinidad drainage are at low divides between the Trinidad and streams flowing into the Carribbean. The rocks at these two points are essentially the same as those occurring at Gatun. They are found in a fresh condition a short distance below the surface and have about the same hardness as the Gatun rock.

At spillway No. 3 the borings failed to discover fresh rock at the depth required for foundation, the material being a clay of decomposition derived from rocks probably the same as those at the other two spillways.

FOUNDATIONS OF THE PEDRO MIGUEL LOCKS.

The Pedro Miguel Locks are built on material that seems slightly less resistant locally than the foundation rock of the Gatun Locks, and may show local differences in settling. It consists of the upper member of the Culebra beds described on pages 21 and 22 and the andesitic dikes that cut them. These dikes have two chief influences as follows: (1) They are harder than the rocks that they cut, so, locally, they will constitute areas of minimum settling, and if proper precautions had not been taken they might give rise to cracks where the concrete structures cross them. (2) The dikes are somewhat in the nature of walls that will tend to lessen the seepage through the slightly porous sediments that they cut. They would greatly lessen seepage were it not for the fact that they are considerably jointed.

DESCRIPTION OF LOCK SITES.

Concerning these lock sites Howe [a] says:

Although the Culebra beds are variable in texture, those in which excavations for the Pedro Miguel Locks will be made are remarkably uniform. They consist of well-bedded sandy shales containing plant remains in a few places, and at some

[a] Howe, Ernest, op. cit., p. 128.

horizons lenticular masses of concretionary limestone are common. The physical properties of the rocks differ but little from those of the rocks at Gatun. Being more argillaceous the shales are naturally less permeable to water, and experience in sinking test pits showed that they were very tough and required more blasting than did the Gatun rocks under similar conditions. This greater toughness is to be attributed to the argillaceous nature of the rock; for the same reason their compressive strength is probably slightly less than that of the argillaceous sandstone of Gatun.

In the vicinity of Pedro Miguel the Culebra beds have a prevailing dip of 5° to 10° to the southeast, varied by sharp local folding; moderate fracturing has accompanied the folding, and slickensides are shown at many points where exposures have been made by recent excavation.

At the point where it is proposed to construct the lower gates a dike of augite-andesite or "trap" crosses the lock site in a direction slightly east of north. It has a width of about 30 feet where exposed on the southwest side of the cut, and its contacts with the shales are clean and sharp. On the northeast side of the cut the dike turns to the north and the contact is more irregular, small apophyses having been thrown off into the shales. The Culebra beds, which are here sharply flexed and considerably fractured, owe their deformation to some extent to the intrusion of the dike; the dike itself, however, is also fractured, and slickensided surfaces within its mass as well as in the shales indicate that movement has taken place subsequent to intrusion, accompanied, it is believed, by minor faulting along the west side of the dike.

These structural features have a direct bearing on the character of the foundations. The dike, on account of its fractured condition, which borings have shown to exist below the lowest points to be reached in excavating for foundations, will be permeable to water. The shales also have been made more or less pervious as a result of their deformation and consequent fracturing. On account of this fracturing local seepage of surface water is to be anticipated, but the character of the Culebra beds northwestward is such that no flow of water is likely to occur through them even when the canal in the summit region is filled with water. Although the general dip of the beds is to the south, borings have shown the rocks to be the clay shales in large part, and as such not water bearing. Furthermore, several intrusive bodies of andesite or basalt cross the canal line between Culebra summit and Pedro Miguel, which will effectually check any flow of underground waters.

The difference in hardness between the trap rock of the dike and the much softer shales of the Culebra beds must be taken into account in planning the lock walls. The possibility of even very slight differential movement in the zone of fracturing and dislocation in the dike and shales adjacent to it should also be considered. By constructing the lock walls in sections, damage which might be done to monolithic walls as a result of such movements or from the unequal settling of foundations of different hardness, will doubtless be obviated.

FOUNDATION OF THE COROZAL LOCKS AND DAM.

The Corozal locks and dam are built in part on the Caimito formation, described on page 25, and in part on what appears to be the upper layers of the Culebra formation. It is somewhat permeable but gives a relatively firm foundation. Of this lock and dam site, Howe[a] says:

> The rocks that underlie the alluvium at depths of from 30 to 60 feet below mean tide are sandy shales * * * Rhyolite tuffs are exposed in the hills at the northern end of the dam site.

[a] Howe, Ernest, op. cit., p. 129.

Mechanical analyses of samples of alluvial materials collected at the site of the Corozal Dam and from the sand bars in the bay beyond La Boca are given below. They were made at the request of the consulting engineers, Messrs. Noble, Stearns, and Freeman, in order to determine the permeability of these materials and their availability for use in constructing the dams.

Mechanical analyses of sand and mud from La Boca, Canal Zone.

[Made at the laboratory of the United States Bureau of Soils.]

Constituent.	No. of sample.					
	2	3	4	5	6	7
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
Organic matter	0.8	1.8	0.8	7.5	5.8	2.1
Fine gravel, 2 to 1 mm	7.1	1.1	7.8	3.1	2.8	18.9
Coarse sand, 1 to 0.5 mm	14.9	.8	39.9	.7	3.3	21.2
Medium sand, 0.5 to 0.25 mm	13.3	.6	26.8	.9	2.5	19.7
Fine sand, 0.25 to 0.1 mm	42.2	2.7	11.0	6.2	23.6	15.7
Very fine sand, 0.1 to 0.05 mm	.8	2.6	.4	3.4	7.1	2.2
Silt, 0.05 to 0.005 mm	1.4	43.1	4.7	31.4	25.9	9.6
Clay, 0.005 to 0 mm	3.0	49.2	9.3	54.4	34.6	12.6

No. 2. Coarse sand, 18 inches below surface, sand bar, La Boca.
No. 3. Alluvial clay from dredge, one-fourth mile south of dock, La Boca.
No. 4. Sand from river bank, near north end of Sosa-Corozal Dam site.
No. 5. Mud from surface of mud flat opposite ship's ways, La Boca near oil station.
No. 6. Mud from dredge, one-half mile south of dock, La Boca.
No. 7. Dry sample, hole No. 14, La Boca Dam, elevation—18.5, 20 feet below surface.

FOUNDATION OF NEW ADMINISTRATION BUILDING, BALBOA.

The new administration building at Balboa, a very heavy structure, was built on a little hill some 50 feet or so above the flat ground in front of it. One corner of the building is rather close to a steep slope, so it was thought that the weight of the structure might cause this slope to slide, and thus wreck the building. It was said that this corner of the building rested on bowlders and clay which might not support the added weight. The writer was detailed to investigate this matter. He found that the supposed bowlders and clay constituted only the weathered surface part of a jointed rhyolite mass. Weathering had progressed from the surface downward along the joint planes, thus leaving semirounded unweathered core masses, which looked somewhat like bowlders, between the weathered zones of the joints. With depth the weathering grew less and the rock became much more solid, so that the building was in no danger whatever. The following report, covering the matter, was then made by the author to the chairman and chief engineer of the Isthmian Canal Commission:

The rock under the surface soil on which the new administration building at Balboa stands is the same rhyolite rock that forms Ancon Hill, and it has about the same degree of jointing. The fragments of this rock, between the joints, are strong and tough. Any slides that might occur in it would be due to steepness of slope and would consist in a mere sloughing off of loose material. There would be no deformation or flowagelike movement such as that which gave rise to some of the large slides in the cut near Culebra.

Toward the surface the jointing in this rock becomes more pronounced, so that the individual pieces between the joints are separated by partings of earthy material. They thus have some resemblance to a mass of bowlders mixed with clay. In reality, however, this is not a bowlder-clay formation.

From the surface downward the rock becomes much less jointed and much more solid. In a cut of any depth or in the side of a mountain, this rock, under its present conditions of jointing, would maintain itself at a slope of 2 on 1, except, of course, the top covering of earth and broken rock, which would stand only at a much flatter angle.

Cross sections show that the maximum slope from the basement floor to the foot of the slope at the railroad is about 7 on 11. This then is well within the limit of safety so far as any slides are concerned.

Now, what effect will the weight of the building, 97 tons per column, have on this mass of rock? If the pier foundations have been put down below the earth and loose rock to the relatively solid, though much jointed, rock below, then there will be no danger of the building causing any slide movement here, for the following reasons:

1. This rock will not deform or flow under any pressure that this building can possibly exert on it, in spite of the fact that in large masses it has not much tensile strength because of jointing. No amount of weight that need be considered would cause a sinking in one part of this material, with a corresponding bulging in another part.

2. At any slope less steep than 2 on 1 this rock (apart from its soil and loose rock covering near the surface) would stand without any danger whatever from slides. The steepest slope from the basement floor to the railway level below is only about 7 on 11, therefore, the margin of safety is ample.

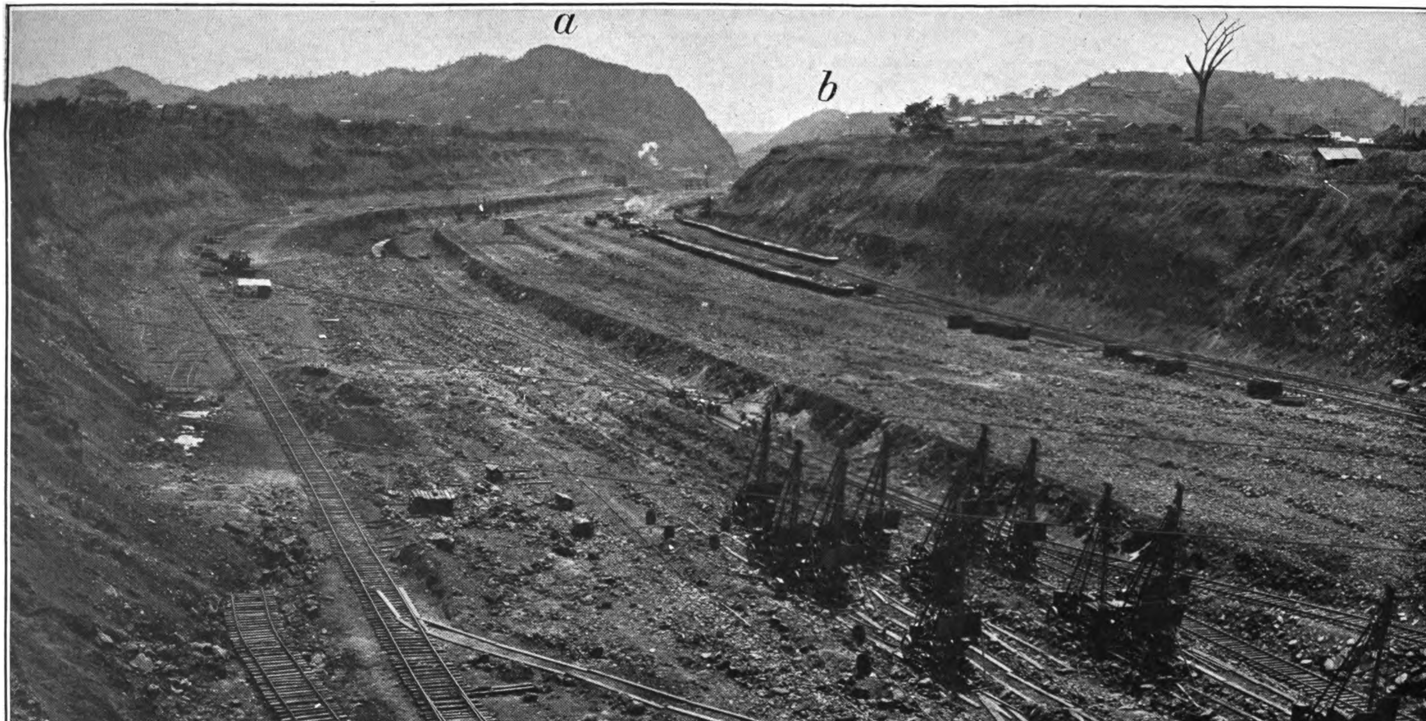
3. Where gravity is able to wedge off masses of rock from any steep slope, then any weight added to such rock masses will increase their tendency to slide. Where, however, the slope is flat enough for any rock mass to be at repose on a solid foundation, then weight (normal to the horizontal) added to it will decrease its tendency to slide. This is merely a special application of the principles illustrated by the parallelogram of forces. The weight of the building, therefore, will in this case not increase the tendency of this slope to slide because the slope is already well within the angle of repose.

4. The weight of the building will, of course, increase the tendency of this rock to deform and bulge up at the base, but, as already explained, it is strong enough to resist any compressional pressure that could possibly be brought to bear on it by any building.

In conclusion, the building is quite safe from the danger of sliding. Of course, this memorandum does not consider the question of the possibility of uneven settling of any part of the building, except to state that if the foundation piers have been put down to the relatively solid (though jointed) rock beneath the soil and loose-rock covering there will be no noticeable settling.

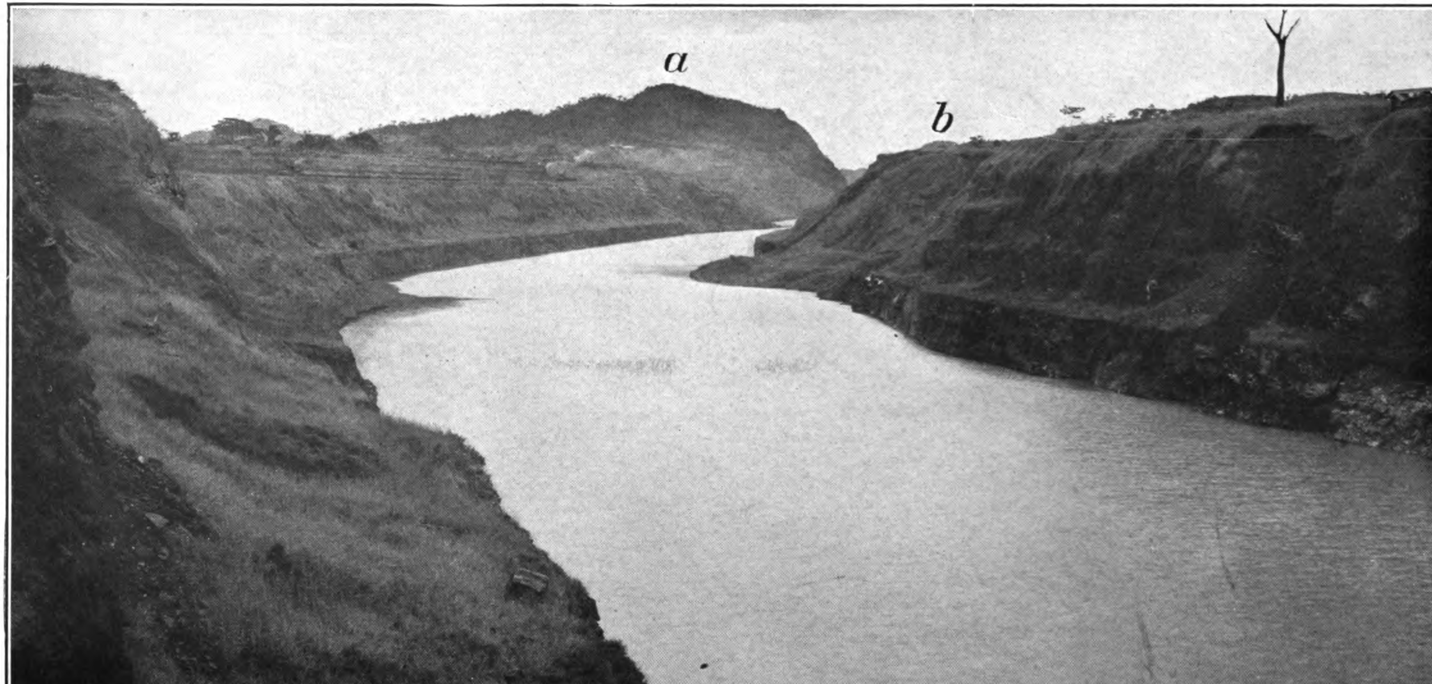
SLIDES.

Culebra Cut is a vast ditch (Pls. XII and XIII) that passes through many varieties of rock in the 9 miles of its length. Some of these are weak and unstable, and where the slopes of the cut were steep and 100 to 300 feet high the weaker rocks locally crushed down to flatter slopes. The flatness depended on the material involved, but, whatever the material, whenever the slope got flat enough the sliding stopped. At no time did the engineering staff constructing the canal believe that the slides were a menace to the ultimate completion and successful operation of the canal, in spite of the fact that at times



CULEBRA CUT IN THE MAKING. LOOKING SOUTH FROM EMPIRE BRIDGE, MARCH, 1911.

a, Gold Hill. *b*, Contractors Hill.



CULEBRA CUT COMPLETED AND WATER IN.

a, Gold Hill. *b*, Contractors Hill.

they were somewhat troublesome. They have made necessary the excavation of about 30,000,000 cubic yards more than was included in the first estimates for Culebra Cut, but they have not in the past and will not in the future endanger the ultimate success of the canal. Because of their importance as a factor in canal construction they are discussed in considerable detail.

ANALYSIS OF CONDITIONS LEADING TO SLIDES.

The following information, with accompanying illustrations, has largely been given by the author in a paper[a] read before the Twelfth International Congress at Toronto, Canada.

Any excavation in the earth's crust sets up stresses in the contiguous rocks, because of the unbalanced pressures created by the substitution of atmospheric pressure for the greater pressure of the material excavated. These stresses are divisible into two distinct groups, as follows: (*a*) Crushing or direct gravity stresses, which have a maximum effect near the toe of the steep slope of the excavation; and (*b*) tensional or flowage stresses, also due, though less directly, to gravity, which exert a horizontal strain toward the excavation and give maximum deformation near the surface (see fig. 6). Now, what might be called the resultant (*c*, fig. 6) of these two groups of stresses may for convenience be called the straining or slide-producing factor.

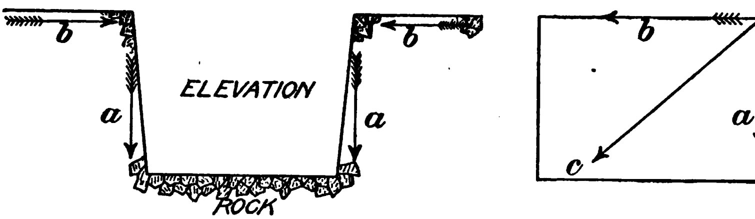


FIGURE 6.—Diagrams showing resultants of deformative pressures.

Two major classes of excavation set up strains in their slopes, or in the continguous rocks, which may result in slides. They are those due to processes of nature, as stream erosion, solution, and fault escarpments, and those due to works of man, chiefly open cuts, underground openings, and submarine excavations. The extent to which any excavation will cause sliding or deformation of the contiguous rock material depends on the following factors:

1. Crushing and tensile strength of large masses of the material involved. These factors vary according to (*a*) the strength of the small component masses, (*b*) the character of the jointing, (*c*) the character of the bedding, and (*d*) the fault conditions.

2. Physical and chemical character of the rock units.

[a] MacDonald, D. F., Excavation deformations: Trans. 12th Int. Geol. Cong., 1913, Ottawa, Canada.

3. Amount and character of the ground water.

4. Earth tremors set up by earthquakes, blasts, passage of railroad trains, or other causes.

5. Other factors, as (*a*) heavy structures contiguous to excavations, (*b*) water freezing in rock openings and wedging off rock masses, (*c*) variation of barometric pressure, and (*d*) earth strains from the kneading of tidal pull.

INFLUENCE OF CRUSHING AND TENSILE STRENGTH OF THE ROCKS INVOLVED.

If a rock has high crushing strength, with few joint or other parting planes, the exposed face will stand almost perpendicular, without shearing or slipping, at any height with which we need to have concern. If it has high crushing strength in small solid fragments, but is much cut by joints, faults, or bedding planes it will not deform or flow but will slough off masses from steep places until a certain angle,

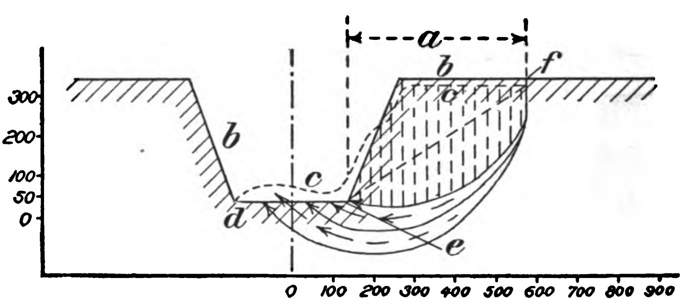


FIGURE 7.—Ideal cross section to illustrate excavation deformations. *a*, Width of zone of deformation, measured from toe of slope; *b*, original surface; *c*, surface after deformation; *d*, bottom of excavation before deformation caused it to bulge upward; *e*, toe of slope, intersection of slope and bottom planes; *f*, crack, or break, caused by deformation of basal part of the block shown with perpendicular broken lines. The curved lines from *f*, with arrow, show approximately the chief zone of deformation and the direction of the motion.

which might be called the angle of repose, is attained. Fissures, faults, or bedding planes that incline toward the excavation and intersect its slopes are planes of weakness and promoters of slides, especially if the bedding planes have shale, lignite, or other greasy rock partings, or if the fault planes are filled with clay or slippery talcose material. Even if such partings are horizontal, relatively light back pressure may push the material that rests on them out into the excavation. Beds of dense, relatively impermeable, greasy clay which slope toward an excavation are especially likely to allow any material that may rest on them to slip off their moist inclined surface.

If a rock has low crushing strength, movement may manifest itself as a deformation or sinking near the excavation, with a slight advance of the lower slope toward the excavation, and a bulging of the bottom (see dotted line, fig. 7). Similar movements have occurred in the Culebra Cut. In most instances, however, such a movement

is only one stage of disturbances that later end in slides, especially if the excavation toward which they are strained be deepened. If a plane such as *ef* (fig. 7) be imagined to extend from the toe of the slope, *e*, through the point of farthest deformation, this plane may not be the final slope at which the material will ultimately come to rest, for such a flat slope might never be attained by sliding. On the other hand, it is not the limiting plane below which deformation or movement of the rocks will not take place, for in certain of the Culebra Cut slides movement well below such a plane has disturbed and weakened the slopes (figs. 7 and 8 and Pl. XIV). The term "angle," as applied to the measure or extent of excavation deformations, is apt to be misleading, so the notation explained below is now much used by engineers.

If an excavation 200 feet deep causes a deformation in the contiguous rocks to a distance of 500 feet in a horizontal direction from a vertical line at the toe of the slope, *e*, shown in figure 7, the phenomenon may be designated as an excavation deformation of 200

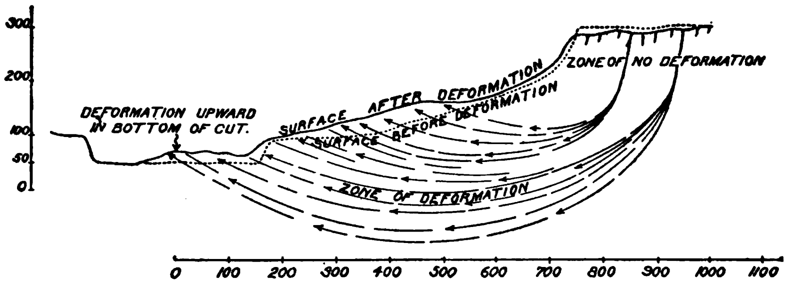


FIGURE 8.—Ideal cross section to illustrate canalward deformation movements.

on 500 feet. This designation indicates not only the depth of the excavation and the width of the zone of deformation, but also the angle of what may, in sand for instance, be the final slope or angle of repose. Engineers now often refer to slopes as being 1 on 1, 1 on 2, etc., meaning 1 unit up and 1 or 2 units over. The designation, however, is a measure only of the angle of slope unless the actual number of units of depth of excavation and width of deformation zone are given. If the rock has a low tensile and crushing strength, conditions would, in the absence of excessive mobility through ground water or other causes, approach those of a talus slope or an excavation in sand, where the slopes would be permanent when they had reached the "angle of repose" for the material involved.

INFLUENCE OF PHYSICAL AND CHEMICAL CHARACTER OF ROCK UNITS.

Excavation slopes in very soft rocks, especially very fine-grained and compact argillites and clays, may remain almost vertical until the excavation reaches a depth of 50 to 125 feet, or until the unbalanced pressure is great enough to cause them to deform. This

deformation destroys the stability of their clayey cementing material, loosens them for the invasion of quantities of ground water, which their fineness of grain had excluded previous to deformation, and induces muddiness and mobility, so that the slope, originally almost perpendicular, may break back to 1 on 10. Deformations closely approaching this have occurred in Culebra Cut in some of the volcanic clay rocks.

Excavations that change the level of the water table may weaken the surrounding rocks by dissolving and loosening their more soluble parts, especially in a region of abundant vegetation, where the ground water contains much carbon dioxide and organic acids. On the Canal Zone the limestones contain many caves, small caverns, enlarged joints, and pitted surfaces, evidences of comparatively rapid solution. The volcanic clay rocks, particularly those of the Cucuracha formation, crumbled rapidly when they were dug from Culebra Cut and exposed to weathering action. Bowlders of this soft rock 2 or 3 feet in diameter have crumbled into clay in less than a year.

The crumbling seems to be due to two causes: First, the outer layers of these clay rocks may absorb rain water and heavy dews, and subsequently be dried out by the hot sun. It is known that after having been once dried out most clay rocks have their absorbing capacity increased much beyond what it was before drying took place. By this process of absorption and drying out, soluble salts are leached out and are sometimes deposited on the outside of the rock as barely noticeable white coatings or as scattered, minute, translucent crystals. These seem to be largely magnesium, iron, and calcium sulphates. This wetting, drying, and leaching loosens up the small individual grains and they drop off, thus removing layer after layer until the whole rock is disintegrated. Second, oxidation, which gives an increase of volume and increases the tendency to disintegrate, may occur. These rocks have a considerable percentage of ferrous iron (up to 3.7 per cent), which is somewhat oxidized to the ferric condition by contact with the atmosphere and with oxygen-bearing rain water.

EFFECT OF GROUND WATER.

Ground water in clay or in weak clayey rocks is an extremely important slide-producing factor. The chief ways in which it aids in the deformation of rock masses are as follows: (1) By greatly increasing the mobility and slippery character of the rock material; (2) by adding weight to a rock mass, which may already be strained toward an excavation; and (3) by weakening a rock through solution and softening. If a relatively porous material rests on top of relatively impervious rock, especially if the contact between the two slopes toward an excavation, ground water or rain will add weight

BULGING OF ROCKS IN BOTTOM OF CULEBRA CUT, CULEBRA, IN FRONT OF LARGE BREAK OR DEFORMATION SLIDE IN EAST BANK BETWEEN STATIONS 1746 TO 1758.

to the porous mass by filling its interstices. It will also soften and weaken the porous material and greatly decrease its adhesive grip on the sloping surface of the relatively impervious rock. The water will descend through the porous material, but will be deflected by the relatively impervious rock; and on this impervious surface will be deposited the mud particles and other lubricating material gathered by it in descent. The contact thus becomes a slippery zone that greatly promotes slides. Even capillary water in a weak rock is a source of danger, especially in fine-grained rocks, for with deformation much of the capillary water may be forced into shear planes, thus giving them increased lubrication. In estimating the sliding or deforming tendencies of a rock careful determinations of its water content should be made, both fresh and air-dried samples being used. The most troublesome slides of Culebra Cut were in fine-grained basic volcanic shales and argillites of fairly massive character. These, after having been air-dried, show 6 to 17 per cent of water and contain considerable finely divided chlorite, a hydrous mineral. Two samples from the Cucuracha formation—the formation in which maximum sliding has developed—were analyzed in the United States Geological Survey laboratory. They showed 12.26 and 9.47 per cent of water when heated below 100° C., and 5.41 and 6.71 per cent when heated above 100° C. Any considerable percentage of chlorite particles is an important weakening factor in rocks, and one that renders them slippery and unstable.

EFFECT OF EARTH TREMORS.

Earth tremors cause deforming movements in rock masses. Many earthquakes cause landslides and rock deformations. Heavy blasts also generate earth waves that loosen and weaken excavation walls and greatly increase their tendency to slide. A blast generates two sets of vibrations, one transmitted through the earth, the other through the atmosphere. The atmospheric vibrations travel seemingly with the same velocity as sound, the earth vibrations much faster. Surface blasts expend a greater proportion of their energy in atmospheric vibrations than do deep blasts. Hence, surface blasts make much more noise and jar houses more than deep blasts, but they have little influence in causing slides. On the other hand, the tremors created by a deep blast help to bring down, even at a considerable distance from the explosion, rock masses already dangerously strained. Two large blasts in Culebra Cut gave the following approximate vibration records: A blast of 2,250 pounds of dynamite, exploded in 14 holes 24 to 28 feet deep, gave a maximum amplitude of 20 millimeters. Another blast of 5,370 pounds of dynamite, exploded in 48 24-foot holes at about the same distance from the instrument, gave an amplitude of 28 millimeters. These records were made on

an imperfect instrument improvised by C. M. Saville, one of the engineers. Its magnification was about 10, so that the amplitudes of the earth waves set up by the blasts were about 2 and 2.8 millimeters, respectively, quite enough to damage seriously a steep slope of brittle rocks already heavily strained. Vibrations from railway trains may also damage slopes that are already in danger of sliding.

EFFECT OF OTHER FACTORS.

Heavy structures contiguous to excavations greatly increase the tendency to slide or cave, as subway and foundation engineers well know. The wedging off of rock masses by the freezing of water in joints, fissures, and interstices is familiar to all geologists who have studied talus slopes in temperate climates. Earth strains, originating from the variation of barometric pressure and the kneading of tidal pull, should not be ignored in the study of excavation deformations. One is apt to forget that the maximum variation of atmospheric pressure near sea level may be more than 4,000,000 tons per square mile. So, if the adjustment of atmospheric pressure in a very large cave or mine lags behind any quick increase in atmospheric pressure at the surface, a considerable strain may be added to the roof of such an excavation.

TYPES OF SLIDES OR DEFORMATIONS IN CULEBRA CUT.

In Culebra Cut there were four distinct types of slides, or excavation deformations, as follows: (1) Structural breaks and deformations; (2) normal or gravity slides; (3) fault-zone slides; and (4) surface erosion.

STRUCTURAL BREAKS AND DEFORMATIONS.

GENERAL DESCRIPTION.

The largest and most important slides developed from structural breaks and deformations. Fortunately, they occurred only near Culebra in a section of the cut not much over a mile long. These deformations first manifested themselves by the appearance of one or of a set of cracks or fissures (fig. 4) parallel or somewhat oblique to the edge of the cut, and from a few yards to some hundreds of yards back from it and from each other. Some of them were traceable on the surface for several hundred yards and gradually developed into perpendicular crevices up to one-third of a yard wide and many yards deep. The second stage of this phenomenon consisted in the settling or tilting of these big block masses that had been divided from each other by the fissures. This movement was a slight and almost even settling (0.1 to 1 yard) of the block or blocks, or a tilting of them toward the excavation, or both. Some of the blocks sank a little in front and tilted up in the rear so that they were a yard above the

front part of the block behind. The third and last stage consisted in the dropping downward of the front block, owing to the failure and squashing out of its base. The whole block then disintegrated and sloughed down into the excavation. This last stage ran its course in a few hours to a few days; the other stages required some months or more than a year to reach completion. The movements of the last and of the second stages were often accompanied by bulging of the bottom and of the lower slopes of the excavation (see figs. 7 and 8 and Pl. XIV). p. 51

p. 51 p. 52

CAUSES.

This type of deformation was due to a primal cause, the unstable geologic condition of the rocks, and an immediate cause, the oversteepness and height of the slopes, the blasting, and other work attributable only to man. The unstable condition of the rocks resulted from several geologic factors, chief among which were: (1) The formations involved consist of soft, weak rocks, comprising massive, partly indurated volcanic clays, friable, bedded tuffs, and soft, brittle, and slippery lignitic shales, all with a relatively high ground water content. These rocks have low cohesion and crushing strength. They are so weak and unstable that locally the unbalanced pressure at the foot of the high slopes was often greater than the resisting strength of the rock. This condition induced deformation, with accompanying slow flowagelike movement, and at times a bulging in the bottom of the cut in front of the slide (Pl. XIV). (2) The rocks have been p. 52 further weakened by faulting and by joint and bedding planes. Shearing zones, due to faulting, trend across the canal, as shown in Plates XV,[a] XVI, XXV, and figure 1. The grinding movement of the rock masses against each other along the faults has been sufficient to shear and crush them for several feet on both sides of the planes of movement. These crushed-rock zones greatly weakened the slopes. (3) Deforming movements caused much rupturing of the weak rocks so that from a dense, fine-grained, relatively impervious condition they locally became much sheared and subject to invasion by large quantities of ground water which tended to leach, oxidize, and disintegrate them. (4) Lignitic-shale beds, especially those dipping toward the excavation, were planes of weakness along which there was a strong tendency for the overlying material to slip. (5) The presence, too, of a considerable proportion of chlorite particles in the volcanic clay rocks tended to lubricate the mass.

The second or immediate cause of this type of slide was chiefly the oversteepness of slopes where the banks were high and the rocks weak and more or less saturated with ground water. In an excava-

[a] Formerly published by the author in an article on "Slides in the Culebra Cut at Panama," Eng. Record, vol. 66, August, 1912, pp. 228-233.

tion through granite the slopes or walls might be made perpendicular for depths of several thousand feet without their crushing in, but if such excavation were carried to a depth of several miles, perpendicular walls could not be maintained even in granite, for the unbalanced pressure at the foot of such walls would exceed the crushing strength of the rock and collapse of the lower part of such excavation would result. The critical depth and steepness for the rocks involved have locally been exceeded in Culebra Cut. The earth vibrations set up by deep, heavy blasting, near slopes already under a severe strain and carrying much ground water, have had a strong tendency to develop slides. The geologic conditions were not sufficiently considered in the first plans for digging Culebra Cut.

REMEDIES.

For this type of slide there was only one remedy that had utilitarian value under the conditions involved, and that was applied. It consisted in making the slopes less steep by removing material from their upper parts until the unbalanced pressure at the foot of the slope became less than the crushing or deforming strength of the rock. To do this, steam shovels were put on the banks to terrace them back on either side of the cut and relieve the strained condition (see Pls. XVII and XVIII). At first sight it might seem preferable to have let the slides come into the excavation and to have shoveled them out from the bottom until permanent slopes were reached, thus saving the expense of much blasting. But
p. 50 51 deformations of this kind weakened the rocks far below the bottom of the excavation (see figs. 7 and 8), and this weakened material would stand only at a much flatter slope than was necessary before it became loosened and disintegrated by deformative movements. Further, as each block or mass crushed down it generally left behind not a gradual slope, but a steep face 12 to 25 yards or more high, which greatly assisted in the generation of other slides. The additional expense and difficulty of shifting and adjusting the railroad tracks, the air pipe lines, the drainage, etc., were also involved. Time figured as a causal factor in these large slides and deformations, for some of them ran their course in a few weeks or months, but others showed cracks for many months or even for years before sliding. Such fissures were sources of weakness which sooner or later, with the deepening of the cut, became troublesome, unless remedied by the reduction of the slopes.

SLIDES IN GOLD HILL AND CONTRACTORS HILL NOT LIKELY.

The highest and steepest parts of Culebra Cut, namely, Gold Hill and Contractors Hill, did not deform and crush, because they are composed of relatively strong rocks of volcanic origin. These more solid rocks extend down deep into the earth and thus constitute vast

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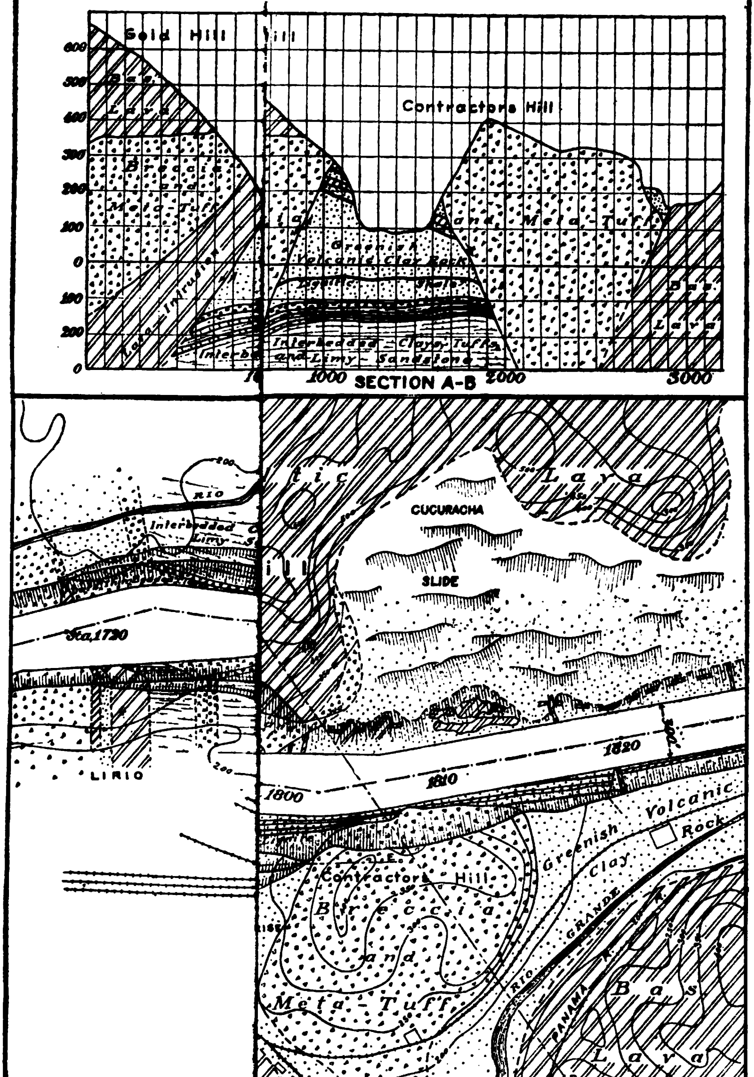


By Donald F. MacDonald.

...LEBRA AND VICINITY.

unyielding buttresses against slides in a section that would otherwise be most susceptible to them. Of course rock loosened by jointing, due in part to weathering and in part to former heavy blasting, from time to time sloughed off from these hard rock masses, but on the whole they have stood solid and immovable.

YARDAGE OF THE CHIEF SLIDES CAUSED BY STRUCTURAL BREAKS.

The chief slides due to structural breaks have taken place in that part of Culebra Cut lying between Gold Hill and Empire Bridge. On the west side in this section of the cut sliding began in October, 1907, and extended so that in all over 70 acres of material moved or was seriously cracked. This movement necessitated the removal of over 11,000,000 cubic yards more than was comprised in the first estimates. This amount, of course, included the material removed from the upper part of the slopes in order to make them less steep and more stable. Sliding began on the east side in this section of the cut about January, 1907. In all some 55 acres of land surface has been in motion here since then, adding close to 8,000,000 cubic yards to the first estimates. The relieving process on this part of Culebra Cut is at this date (January, 1914) not yet quite complete, and a considerable amount still remains to be moved before perfect stability of slopes will prevail.

The structural-break type of slide is therefore responsible for the movement of about 19,000,000 cubic yards of material over and above that included in the first estimates.

PREVIOUS STATEMENT REGARDING STABILITY OF HIGHEST PARTS OF CULEBRA CUT.

Before the subject of the structural-break type of slide is left, it might be well to set forth the salient features of a memorandum regarding the stability of the places of maximum height of slope in the Culebra Cut, especially at Gold Hill and Contractors Hill. The memorandum was prepared by the author in the fall of 1911 in response to a more or less current opinion to the effect that these hills would, because of their great height and steepness, deform their bases and crush down into Culebra Cut as great structural-break slides. An examination of the geologic conditions showed that such would not be the case, as mentioned in the excerpts that follow.

Three sections are shown on Plate XV, namely: A–B, Gold Hill, through Contractors Hill, to the lava slopes beyond the Panama Railroad; A–C, Gold Hill to Mount Zion Reservoir; and D–E, from a point northwest of Col. Hodges's house to Contractors Hill. These sections are drawn to depths of about 200 feet below sea level. The rocks shown at that depth are known to occur there from the fact that they outcrop at certain angles on both sides of Gold and Contractors Hills, and a projection of both angles and of the probable curvature of the beds locates them at about the depth indicated. That stronger limy sandstone rocks occur below the green clays in the vicinity of Contractors Hill is certain; that they occur at the exact depth shown on the cross section is not certain, for they may be, say, 25 feet higher or lower than the

elevation there recorded. The presence of these rocks has a direct relation to the slide problem, for they are strong enough, except where faulted, to limit the downward depth of any deformative movement of the weak green clay rocks on top of them. Unfortunately, southward of station 1762 they are too deep to prevent present deformative movements of the green clay rocks above them. Northward of that station they come to the surface for a considerable distance, and their presence is marked by sustained slopes between stations 1762 and 1749.

Contractors Hill.—Contractors Hill is a cap on top of a basalt plug which came up from a depth of probably much more than a thousand feet. It contains fragments of basalt, and consolidated at an elevation above the stability of its foundation. Gravity, cooling, and time were factors that caused a settling back to equilibrium, as it has done. What is the evidence of this settling back? Plate XIX shows a part of a shear plane that extends around the canalward side of Contractors Hill, and must entirely surround it. On this plane is a hard fragment *c;* inclosed in a softer matrix and behind it (above) is a sloping little ridge of softer material. This hard fragment, held fast in a softer matrix, had a part of this matrix scrubbed away from all sides of it except that on the upper side, the side opposite to the direction of its motion. This and other similar data absolutely establish the fact that the last movement of this mass was downward. The amount of this downward motion is indicated as follows: The zone of crushed rock *d* is about 10 feet wide. This wide zone of rock has been crushed and highly sheared by the downward motion, and the experience of geologic observation of many different kinds of faults is that shear zones 10 feet wide, under conditions similar to these, result only where the differential movement of the rocks has been, say, more than 300 feet. Now, it is evident that if this great roughly circular mass of rock, after having come up, settled back through the weaker surrounding rocks a distance of 300 feet, its foundation must be at least a thousand feet below the surface. Therefore it seems certain that the unbalanced pressure caused by the excavation of a few hundred feet of the surface material will never result in any disturbance to such a deep foundation as that of Contractors Hill. Of course local masses of rock will crush down from its steep slopes occasionally, and some of these may be rather extensive, but the hill mass as a whole will remain perfectly solid.

Gold Hill.—Gold Hill, in its origin and composition, is somewhat similar to Contractors Hill. The top of it, however, is covered with a thick flow of hard basalt, and a massive basalt dike has come up around its periphery on at least two sides (see Pl. XV). The downward motion of Gold Hill is evidenced by the fact that the small lava breccia mass *d′*, Plate XX, has come down from, and is a fragment of, the lava breccia *d*. With other sheared material, it has been dragged in by the downward frictional pull of the hill mass. The sheared zone *c* around the visible portion of the margin of the hill is as great as that around the margin of Contractors Hill, showing that the downward movement of both masses has been almost equally great, and that their foundations are undoubtedly several hundred feet below sea level. Gold Hill is also greatly strengthened by the massive lava dike that comes up on at least two sides of it, as shown in figure 1. The origin of this lava rock (basalt) has certainly been more than a thousand feet below sea level, and its strengthening influence is very great.

Faults.—The extent, direction, and dip of the chief faults in the vicinity of Culebra are shown on Plate XV. Most of these diverge outward from the contact zone between the two solid masses, Contractors Hill and Zion Hill. These fault planes have greatly weakened the already weak, friable, greenish clay rock, and for this reason the "storm center" of "breaks" and slides for Culebra Cut will continue to be here until permanent slopes are finally established.

Probable limits of sliding ground.—Lines representing the probable limits of sliding ground are shown on Plate XV. Such lines must necessarily be more or less approximate. In some places slides may reach beyond these approximate limits, and in other

FAULT ZONE NEAR CULEBRA.

a, Fault plane cutting across canal. *b*, Zone of weakened sheared rocks. *c*, Limy sandstone beds which are stronger than the dark carbonaceous clay beds under them (see Plate XV, 1*b*). *d*, Dark carbonaceous clays and bedded tuff (Plate XV, 1*b*). Note how rocks on left of (*b*)—the overhang of the fault plane—have slid into the Cut.

TERRACING ON BOTH SIDES OF CULEBRA CUT, NEAR CULEBRA, TO RELIEVE STRAINED CONDITION OF THE SLOPES. VIEW TAKEN FROM CONTRACTORS HILL, LOOKING NORTH.

a, General offices, Culebra.

TERRACING TO RELIEVE STRAINED CONDITIONS OF SLOPES, EAST SIDE OF CULEBRA CUT, STATIONS 1735 TO 1765.

FAULT PLANE AT CONTRACTORS HILL.

a, Contractors Hill mass, which seems to be surrounded by the fault plane *b*. The motion of the hill mass was downward, as shown by the protected little areas of softer matrix behind (above) the hard basaltic fragments in the hill mass, as shown at *c*. The sheared zone *d* is here over 10 feet wide.

places these limits may not be reached. On the whole, however, it is believed that these lines represent pretty closely the area of ground that is likely to be disturbed. This area may be narrowed down somewhat by the relieving excavation work which may be completed, say, before the close of the next dry season. It will be noted that these lines converge on the cut about station 1760, and are comparatively restricted for the next 1,000 feet northward. This is due to the strengthening effects of the sandy limestone and limy sandstone beds that occur toward the surface there. The western slope in the vicinity of 1740 to 1745 will probably be disturbed to a rather wide extent, but the sliding there will be somewhat superficial, and large movements of the break type should not occur. These superficial slides are due largely to the presence of the lens of greenish, sandy clay rock shown on Plate XV. The upper part of this becomes muddy, and any material that may overlie it easily slips into the cut.

On both sides of the canal in the vicinity of stations 1737 and 1747 faults have disturbed the strata. These faults, however, are mostly at right angles to the cut, and will therefore be much smaller factors in producing slides than would be the case if they cut across with diagonal trend. The slides, then, along near the above-named stations give no evidence of assuming very large proportions. Northward of these stations in the region mapped the sliding problem grows less until the Empire breccia is reached. This breccia as a whole will not slide, though local masses of rock may fall from its steep slopes. In conclusion, it may be said that the crack that developed under and disturbed the Club House, Culebra, was due to renewed movement along an old minor fault plane. All the ground under the Club House may slide, but the northwest corner of the building is not more than, say, 100 feet from ground that will not slide.

Summary.—In summary, maximum sliding in Culebra Cut will occur and is occurring on the west slope about opposite the Isthmian Canal Commission Chapel, because the already weak rocks there have been greatly weakened by faults which trend diagonally across the cut. Relief excavation work vigorously pushed ahead in this vicinity will greatly ameliorate conditions.

PROBABLE LIMITS OF SLIDING GROUND.

In spite of much subsequent deepening of Culebra Cut with some flattening of its slopes, the "probable limits of sliding ground" shown on Plate XV (made in 1911) hold good, with some exceptions, at the date of writing, August, 1915. In a memorandum to the Chairman and Chief Engineer of the Isthmian Canal Commission, dated May 10, 1913, the writer predicted a serious slide just north of Gold Hill, the outer limits of which would be at some cracks 1,500 feet back from the center of the canal. This slide will be far outside the limiting line mentioned above. A somewhat unlooked-for slide on the east side of the cut, between stations 1746 and 1758 in February, 1913, was caused by two large fault zones which were masked by sloughing material so that their dangerous character was hidden until the slide came down.

SUMMARY.

In summary, then, the structural-break type of slide was due to oversteep slopes in places where the banks were high and the rocks weak. The remedy was to unload the unbalanced pressure and to reduce the slopes. The ends sought to be accomplished by the remedy were a reduction of the amount of excavation that otherwise would be necessary and noninterference with tracks, drainage, etc.

The slopes stood at a much steeper angle before being disturbed than after they had been weakened by deformation.

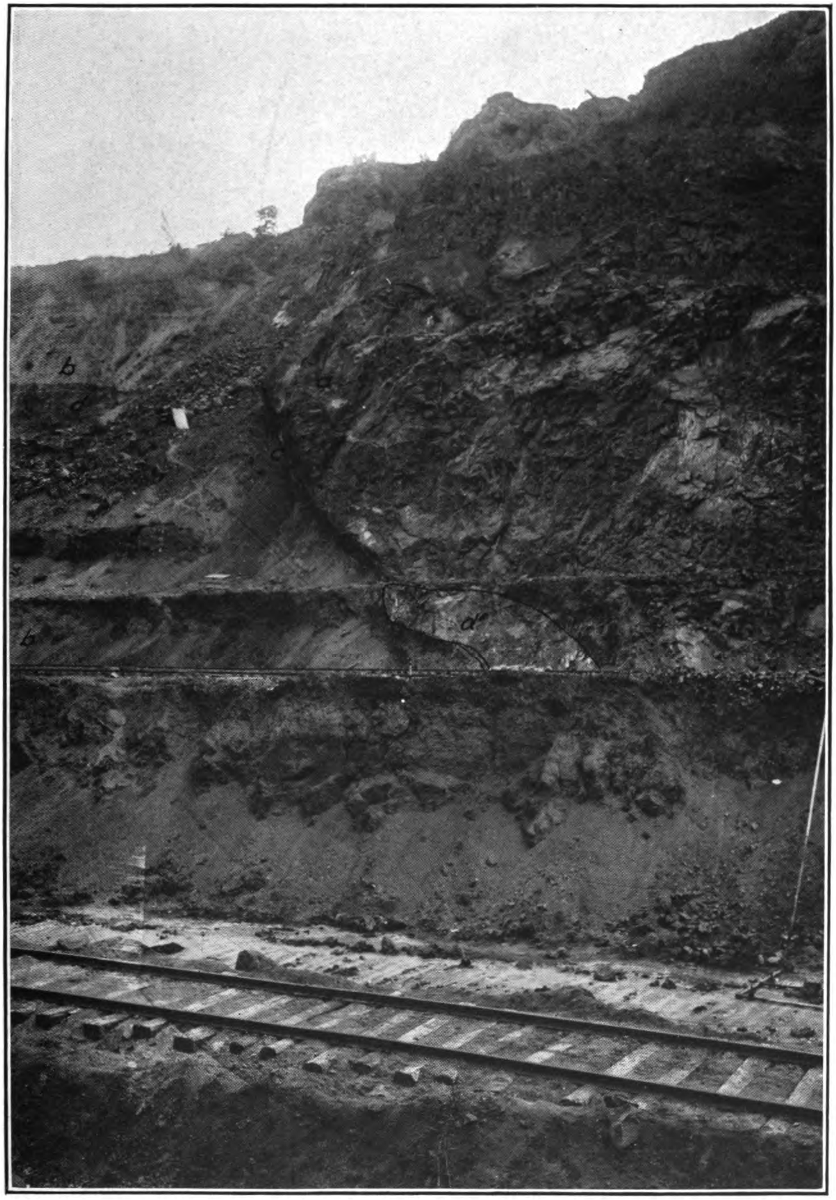
NORMAL OR GRAVITY SLIDES.

The normal or gravity type of slide was due to several factors. Locally along Culebra Cut porous material lies on top of relatively impervious clay, shale, or igneous rock. Rain and ground water saturated this porous mass, but were impeded in their downward course by the relatively impervious rock. Thus a muddy, slippery zone was formed along the plane of contact between the pervious upper and impervious lower materials. When this plane sloped toward the excavation, or where there was thrust or head of pressure toward the excavation from higher ground in the rear, a slide of the normal or gravity type often resulted (Pl. XXI and fig. 3). Where bedding and joint planes dip toward the excavation and intersect the slopes they greatly assisted gravity to wedge off rock masses. This type of slide had certain distinguishing features. The rocks were not deformed or weakened below the plane of actual sliding. The sliding material moved off a relatively solid base and this base was not pulled down or squeezed out by the frictional drag. Hence these slides were not as destructive as the break-deformation slides were, for they did not weaken the slopes below the plane of actual sliding. No saving of excavation could ordinarily be accomplished by removing material from the upper parts of such slides. It was better and cheaper to let them run their course and remove them from the bottom of the cut. Drainage was almost the only remedial factor that could be applied to them. The Cucuracha slide (Pls. XXIII and XXIV), active at intervals since the French company began operations, was the worst slide of this type.

Slides of the normal or gravity type have been relatively numerous, but, with the exception of Cucuracha slide, less important and much smaller than those of the structural-break type. The following list of these slides shows approximately how much material each involved:

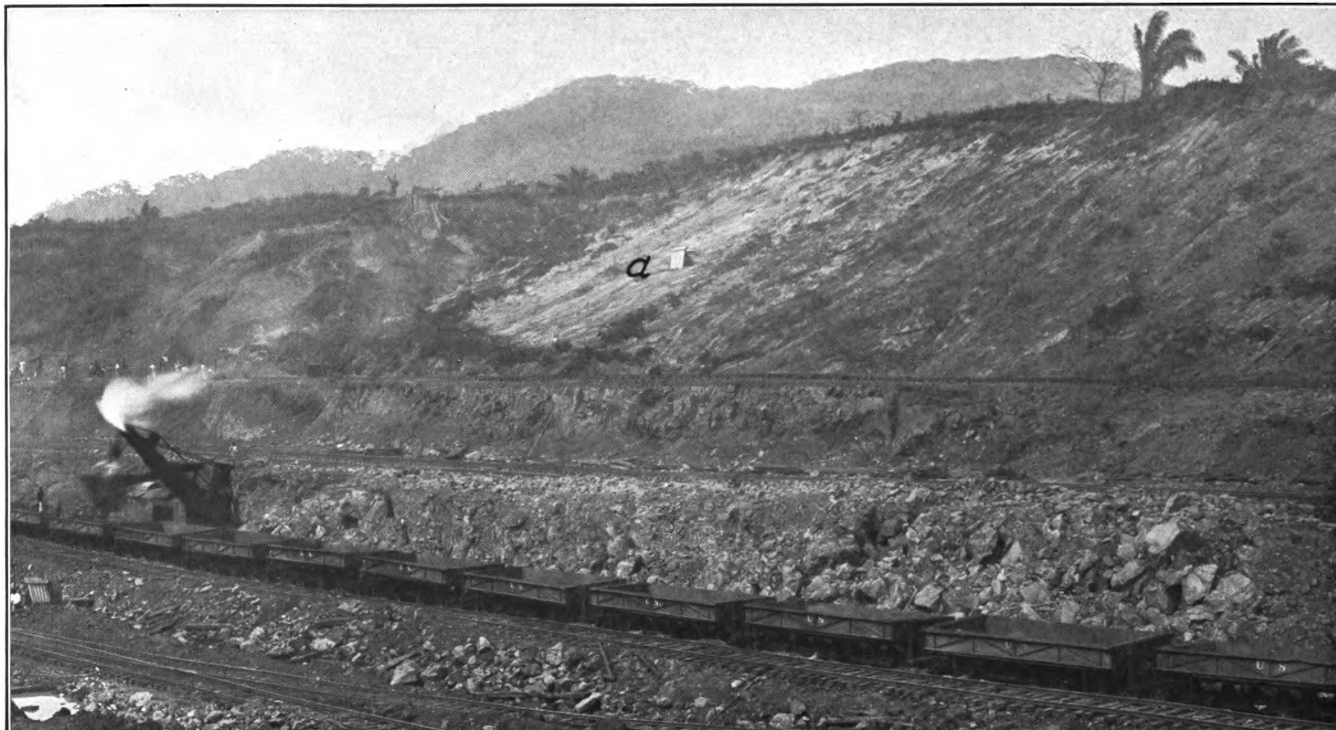
Extent and location of past slides in Culebra Cut.

Location.	Date when slide first developed.	Quantity of material excavated.	Area of slide.
East side:		*Cubic yards.*	*Acres.*
Buena Vista	May, 1912	68,000	1.2
Las Cascadas	February, 1908	583,000	11.5
Whitehouse	October, 1908	609,000	6.0
Powder house	October, 1909	613,000	5.8
Empire	May, 1912	1,213,700	20.0
Cucuracha	July, 1905	5,359,500	50.0
Cucuracha village	September, 1911	231,000	4.0
Paraiso	March, 1907	385,000	5.7
Pedro Miguel	January, 1913	13,800	.2
West side:			
Whitehouse yard	June, 1912	75,000	1.0
Cunette	September, 1910	67,000	.9
Total		9,218,000	106.3



FAULT PLANE AT GOLD HILL.

a, Northerly edge of Gold Hill mass, part of the basalt dike which forms the northern and western periphery of this hill; *b*, Cucuracha formation; *c*, fault zone, which extends around hill mass. *d*, old lava flow; *d′*, mass of old lava pulled down from *d* (over 100 feet) by frictional drag of hill mass, as it was faulted downward in late geologic times.



SLIDE NEARLY OPPOSITE LAS CASCADAS, ACTIVE IN 1908 AND 1909.

Relatively porous rock became saturated and slid off the comparatively impervious underlying rocks (a) toward the canal.

For nearly a year, in 1912, the Cucuracha slide showed little movement, owing to the fact that it was held back by large dikes of basalt (see Pl. XV and fig. 3). These seemed quite large enough to limit further sliding to a few hundred thousand cubic yards. However, when the cut in front of these sustaining dikes had been deepened to the final level the earth pressures behind them became so enormous as to shear and crush the dikes and start almost 2,000,000 cubic yards of material moving. The pressure developed by this slide and the flatness of the slope on which the material moved (see figs. 3 and 9 and Pl. XXII) were most astonishing. However, in spite of this the dikes would almost certainly have held but for the excessive jointing that had rendered them much weaker than their size indicated. Now that the cut is down to final depth in front of this slide the latter has entered its last stage of activity, and a year or two of dredging should entirely eliminate the menace of this slide.

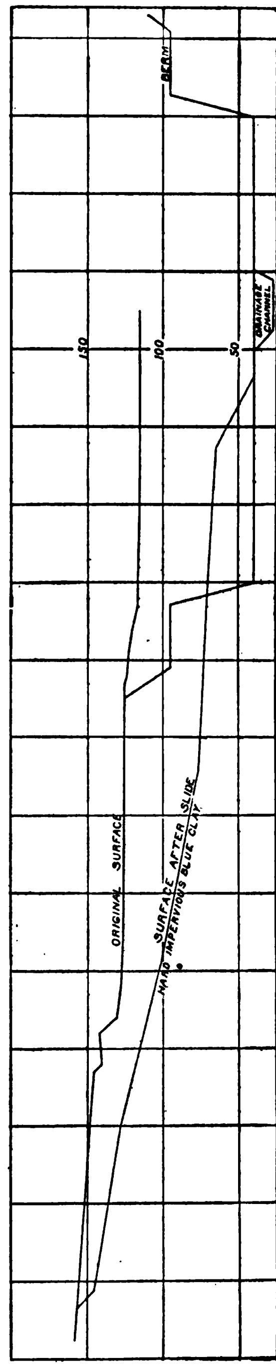


FIGURE 9.—Cross section of slide shown in Plate XXII.

FAULT-ZONE SLIDES.

The third type of slide was that occasioned primarily by sheared and weakened zones in the rocks, due to fault displacements. As the rock masses moved past each other, in the adjustment of earth blocks in late geologic time, the frictional pressure or drag was often great enough to crush and shear the material for several feet on each side of the plane of movement (Pls. XV, XIX, XX, and XXV). Where faults of this kind cut diagonally across the canal large masses of rock in the acute angle between the fault plane and the plane of the canal slope generally fell out into the excavation. Where the fault plane had a considerable dip it left a mass of rock, with a narrow base and wide top, resting insecurely against

the slippery crushed rock of the fault zone and quite separated by this crushed material from the solid rock on the other side of the break. This development, of course, threw an extra strain on the base of the faulted-off mass, and if that failed, the whole block crushed down.

The most notable slides of the fault-zone type were the La Pita slide (Pl. XXVII) and the large slide (Pl. XXVI) that occurred about 600 feet north of La Pita between Empire and Las Cascadas on the east side of the canal. In both cases a brownish breccia locally covers a dark-gray volcanic agglomerate to a depth of 60 feet, the whole forming a steep bank of 90 feet at La Pita and of over 125 feet in the case of the other slide. In each a fault (Pl. XXV) crosses the cut, making a diagonal angle with the trend of the canal. The differential movement of the rocks along this fault plane had sheared and crushed them. This plane of shearing dips northerly at an angle of about 65°, thus leaving a weakened overhanging mass which rested insecurely against the rocks from which it had been faulted off. A diversion ditch on top of the bank came within 100 feet of the slope here, and the water from this ditch leaked out in places along the breccia-agglomerate contact, but chiefly along the sheared fault zone. In the case of the northmost slide the basal agglomerate contained volcanic mud-lava flows which on cooling assumed columnar jointing (Pl. XXVIII), and these joints afforded channels for the invasion of seepage and ground water. The water softened the agglomerate, especially down near the foot of the slope, where it was already weakened by the fault zone and under great strain from the overhanging mass. The result was that the basal agglomerate failed and crushed down under the weight of a huge block of the breccia that contained about 20,200 cubic yards in the case of the La Pita slide, and 300,000 cubic yards in the case of the slide 600 feet north of La Pita.

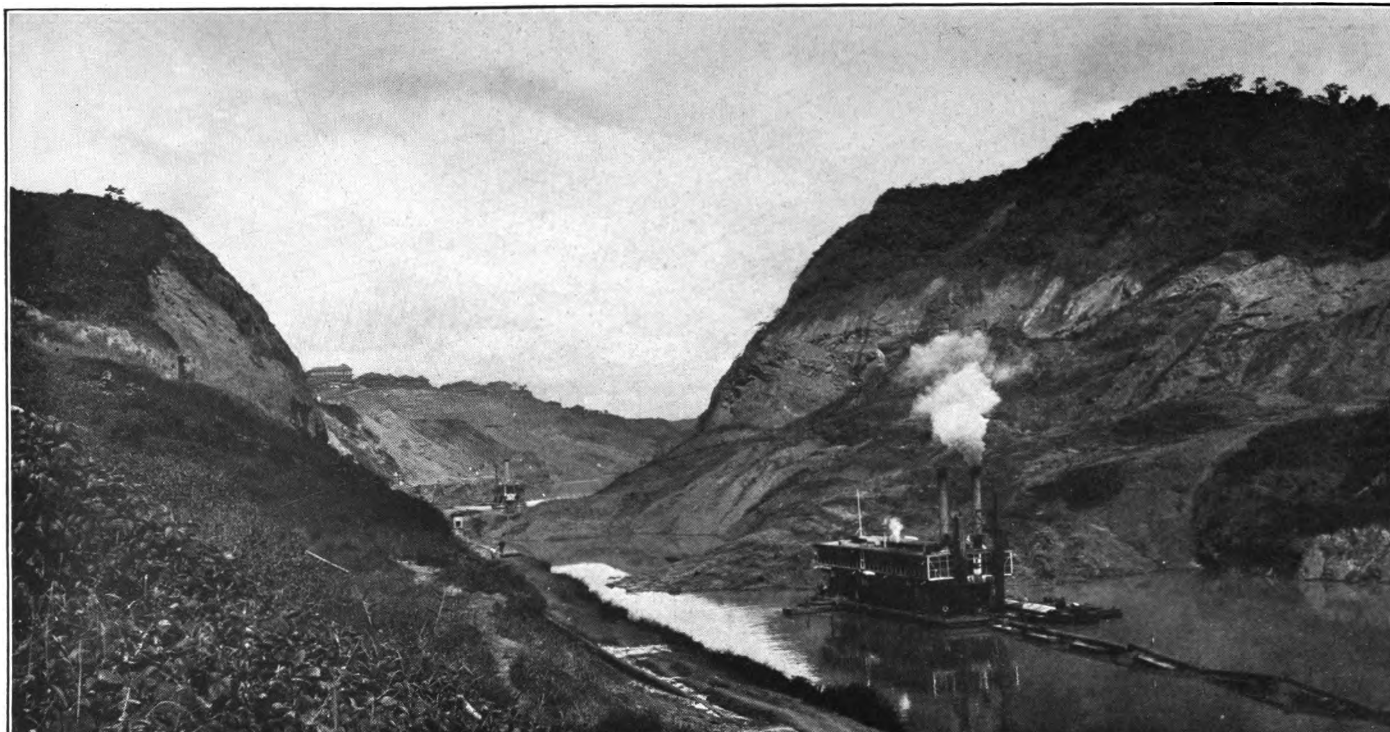
Among slides of this type may be classed that which occurred near the division office, Empire. It was due to a fairly large fault which trends across the canal and has considerably sheared the rocks on both sides of the cut. Because of the higher slope more sliding occurred on the west than on the other side (Pl. XXIX). Here the crushed basaltic rock which forms the ridge on which the office stands (building near left side of Pl. XXIX) gradually slid on a steep, slickensided slope of clay and sheared rock, letting about 278,000 cubic yards of material into the cut.

The fault-zone type of slide, unlike the others, occurs in rocks strong enough to stand at a steep slope except that large blocks of them are weakened by diagonal canalward sloping faults, which leave overhanging parts of large rock masses resting insecurely against slippery fault-zone material. Slides of this character were not common. The only remedy for them was to lessen the slopes in the vicinity of the

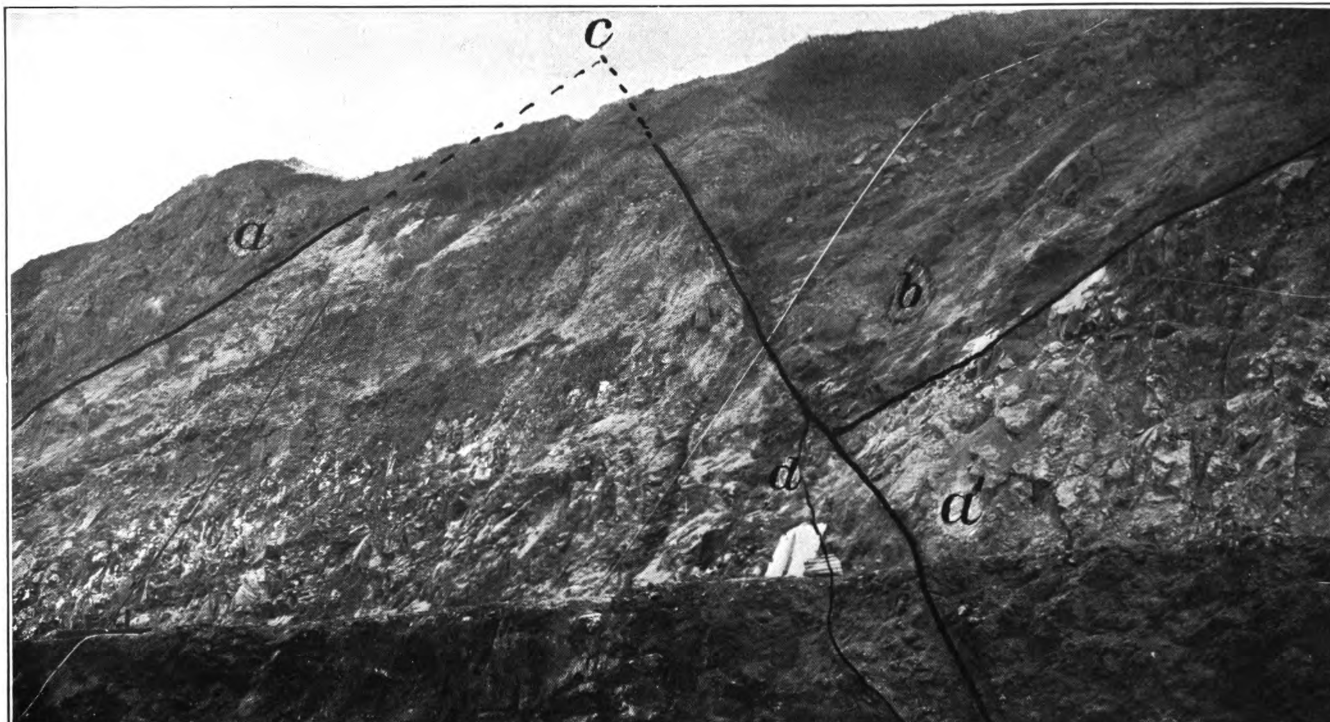
SLIDE NEAR CUCURACHA VILLAGE, EAST SIDE OF CULEBRA CUT.

Slide included 231,000 cubic yards.

CUCURACHA SLIDE, LOOKING NORTH FROM WEST BANK, SOUTH OF CONTRACTORS HILL, FEBRUARY 7, 1913. NOTE STEAM SHOVEL TILTED OVER BY SLIDE.



DREDGES WORKING ON CUCURACHA SLIDE AFTER THE WATERS HAD BEEN TURNED INTO CULEBRA CUT.



FAULT OR BREAK IN ROCKS ON WEST SIDE OF CULEBRA CUT NEAR STATION 1652.

This fault zone trends across the Cut and was the chief factor in causing the big slide shown in Plate XXVI. *a*, Coarse breccia. a^1, Coarse breccia (same as *a*) has slipped down about 50 feet along the fault plane *c*. *b*, Overlying agglomerate. *c*, Intersection of fault plane with slope of Cut. *d*, Minor slips.

fault zones and to prevent excessive water from seeping into them where practicable. There might be cases in which it would pay to reinforce these weak zones with steel and concrete to prevent initial motion, but no such case came to notice in the work on the Canal Zone.

SLIDES DUE TO EROSION.

The soft and easily weathered rocks of Culebra Cut are much trenched and washed by heavy rains where they slope steeply and are unprotected by vegetation. The rapid weathering of these rocks is due to the peculiar effects of leaching and oxidation, as explained on page 52. Each heavy rain removes the disintegrated soil from the slopes of the excavation, fresh surfaces being exposed for further weathering action. It is estimated that the sediment washed into Culebra Cut in this way during the first few years would cover the bottom of the cut to a depth of 2 inches or more each year. This would amount to something over 65,000 cubic yards, which, at 25 cents per cubic yard for dredging, would add over $16,250 per year to maintenance charges.

REMEDIES.

Fortunately, the luxurious growth of vegetation that characterizes the region provides a remedy for erosion, for the slopes will suffer relatively little when carpeted with grass and shrubs. It was therefore proposed to promote the growth of vegetation on the permanent slopes of the canal where necessary. Such vegetation will have no effect on the large slides, but will minimize the wash from heavy tropical rains. In order to alleviate the weathering and washing effects in certain steep parts of the cut, a thin veneer of cement was spread on the slope from a spraying cement gun. This plan was not a success, however, because within a few months the thin veneer of cement began to crack and peel off, owing the the following causes: (1) Oxygenated surface waters seeped through the cement and through the rock and oxidized the rock along its contact with the cement, thus causing the adhesive zone, or contact, to become loose and crumbly; (2) leaching by ground water loosened the rock and tended to destroy the adhesion of the cement veneer; (3) irregular swelling of the rock due to oxidation, adjustment of pressures, etc., cracked the cement veneer and further weakened it; (4) blasting vibrations tended also to crack and scale off the veneer.

SLIDES DUE TO WASH OF STEAMERS.

Another erosion problem arising in connection with soft rocks results from the wash of steamers passing through the canal. Any protective covering used to obviate this will have to be designed with some understanding of the geologic conditions of the rocks that it is to protect. For instance, the rocks will swell somewhat

with oxidation and they will crumble a little wherever ground water can leach out their soluble salts. As time goes on, there will also be some slight adjustive movements, created by the new conditions of rock pressure. All of these movements will be different, as the character of the rock changes from place to place.

The erosion from wash of steamers may probably be best handled by allowing it to take its course and by dredging out the material annually accumulating from that cause.

SOME SLIDES OUTSIDE OF THE CANAL ZONE.

SLIDE NEAR PORTLAND, OREG.

One of the most notable slides outside of the Canal Zone of which the writer has knowledge is that at Portland, Oreg., described by Clarke.[a] Clarke's paper sets forth the difficulties of the Portland water department with sliding ground on the face of a clay slope of considerable extent. It seems that two reservoirs were built on this slope and were lined with concrete. Cracks in the concrete at first puzzled the engineers, but were finally referred to slow, sliding movements of a large area of ground. Many bore holes and several shafts were sunk to ascertain the cause and nature of the motion. From these it was found that an enormous mass of earthy material 50 to 110 feet thick was slowly creeping down the hill. The mass was moving on certain moist, slippery planes, or shear zones, close to bedrock, or else on slightly sloping beds of dense slippery clay, which was somewhat impermeable to ground water. When these sliding planes were intersected by bore holes and shafts they gave off large quantities of ground water. This showed that the ground water was checked in its descent by the more dense material, and that it then tended to flow over the surface of the relatively impermeable layers, thus creating a slippery, somewhat weakened zone along which sliding developed. The rate of the motion was exceedingly slow, and it varied directly as the rainfall, as is shown in the following table:

Relation of slide near Portland, Oreg., to rainfall.[b]

Time of observation.	Total rainfall.	Total movement.		Average maximum movement per month.
		Minimum.	Maximum.	
	Inches.	*Feet.*	*Feet.*	*Feet.*
December, 1895, to May, 1896	27.58	1.09	1.30	0.22
June, 1896, to November, 1896	18.08	.25	.45	.08
December, 1896, to May, 1897	21.74	.71	.84	.15
June, 1897, to November, 1897	18.69	.03	.14	.02
December, 1897, to May, 1898	25.33	.05	.15	.03
June, 1898, to November, 1898	13.12	.00	.03	.01

[a] Clarke, D. D., A phenomenal landslide: Trans. Am. Soc. Civ. Eng., vol. 53, December, 1904, pp. 322–412.

[b] The readings represent the minimum average movement at 8 different points along the center of the slide.

SLIDE ON EAST SIDE OF CULEBRA CUT, NEAR STATION 1652. INCLUDED NEARLY 300,000 CUBIC YARDS OF ROCK. CAUSED LARGELY BY WEAKENING EFFECTS OF FAULT SHOWN IN PLATE XXV.

LA PITA SLIDE.

a, Diagonal fault plane which greatly weakened the rocks and through which water seeped from the diversion ditch; *b*, smaller fault plane which also weakened the rocks; *c*, location of the diversion ditch; *d*, breccia, comparatively strong rock; d_1, block of 20,200 cubic yards of rock which crushed down; *e*, volcanic agglomerate—the rock which failed because of the fault zones, the weaking effect of seepage along the fault zones, and the steepness and height of the slope.

In length the sliding ground was about 1,700 feet and in width over 1,000 feet. Its surface area was about 29 acres and its bedrock area 23½ acres. In volume the sliding mass contained 3,400,000 cubic yards, or an approximate weight of 4,600,000 tons. It slid on a remarkably flat slope plane of about 1 on 9.

Because of the large amount of ground water contained in the shear planes along which sliding took place, and because the rate of movement seemed to be controlled somewhat by the precipitation, it was decided to try to stop the slide by means of drainage. A continuation of the slide would have cost the city over a quarter of a million dollars, so it was decided to drive a main tunnel with several branch tunnels, so that the planes of sliding could be drained. In all, 2,507 feet of tunnel was driven, at a cost of $14,161, or $5.65 per foot. This main tunnel and the branch tunnels were connected with the shafts that had been sunk and effectively drained the region. The result was that the sliding stopped, and the ground has scarcely moved since that time.

SLIDE ON SLOPES OF DES MOINES RIVER, IOWA.

Another example of drainage that effectively stopped a large slide in clay is one on the slopes of the Des Moines River, Iowa, described by Merrick.[a] In this instance some unusually heavy rains caused a large area of glacial clay, overlying shales, and coal beds to creep down from the slope toward the bed of the Des Moines River. The movement involved the end pier of a steel bridge of the Chicago & North Western Railway. The remedy applied was to construct three main drains with laterals. These were 5 feet wide on the bottom and 4 to 10 feet deep. They were filled with broken rock, on top of which was placed a layer of willow brush, and the whole covered with the material excavated. During the construction of the drains the ground moved toward the railroad about 2 feet, the plane of slipping being about 8 feet below the surface. The report is that the drainage effectively checked the slide.

The discussion explaining this slide speaks of several instances where landslides on European railroads had been either obviated or greatly benefited by drainage.

SLIDE IN BRITISH COLUMBIA.

In an irrigation district in British Columbia the Canadian Pacific Railway cut through some hard clay that resembled soft soapstone. The climate was dry, and the clay stood up well in the railway cuts and gave no sign of sliding. Some years later irrigation was intro-

[a] Merrick, A. W., The clay slide at the Boone Viaduct, Boone, Iowa: Jour. West. Soc. Eng., vol. 11, June, 1906, pp. 332–350.

duced, and shortly after large landslides began to occur along the railway line. Investigation showed that under the influence of moisture the hard clay became soft and lost its cohesion. A test was made in which some of the dry clay was placed upon a plate and water dropped upon it. It absorbed 50 per cent of its own weight of water without any change, but when 60 per cent of water had been absorbed it became almost fluid and completely collapsed. Sandy clays weighing 113 pounds per cubic foot when dry are said to have been found by some English experimenters to readily absorb water until they became a sludge with an angle of repose of 16° and less. Argillaceous silt absorbed 53.5 per cent of its volume without altering in form, but after absorbing 78.5 it disintegrated and became a slurry. Certain blue clays deformed at slopes of 1 on 5 when saturated with water, and other more plastic clays showed flowage or deformation at slopes as flat as 1 on 7.

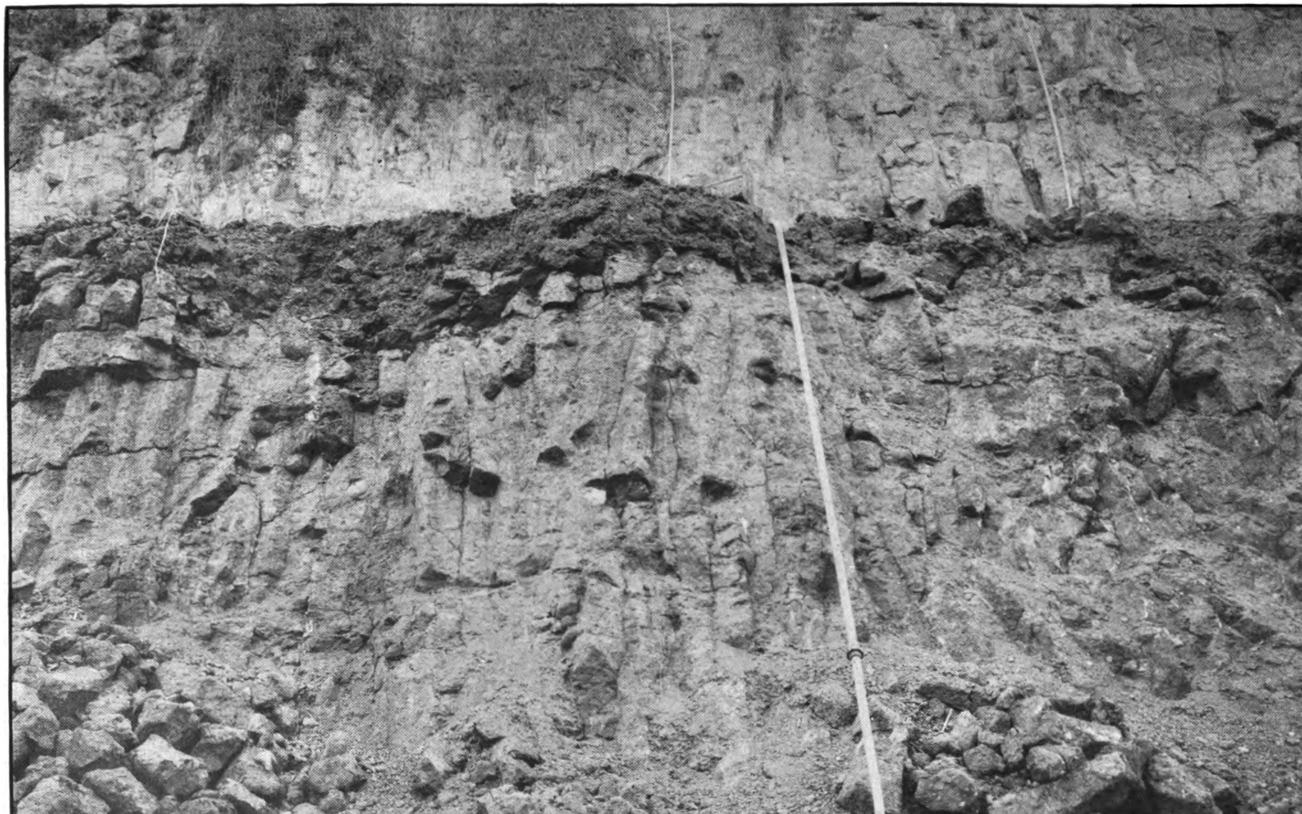
SLOPES TO MINIMIZE SLOUGHING AND DEFORMATION.

The character of material cut by excavations varies over a wide range, from granite to mud. Theoretically, then, the slopes should vary from perpendicular to almost horizontal. Because of varying conditions it is nearly impossible to set down the exact figures to which slopes should be made to conform for security and minimum excavation. The figures given herein are based largely on observation of railway cuttings and mountain and canyon slopes in Central America and in the United States. The figures are not by any means final, and any discussion that they may cause will be welcomed as the first step in the best way to gather more information on the subject. It is hoped that the engineer and the geologist may thus be aided in estimating the distance from any excavation to which deformations are likely to extend, and especially that more data for estimating the cost and yardage of excavations may be available.

SLOPES WHERE ROCKS MAY SLOUGH BUT WHERE THEY WILL NOT DEFORM BY FLOWAGELIKE MOVEMENT.

Different type conditions under which rocks will slough but will not deform by flowagelike motion are postulated below:

1. Given solid rock of relatively high crushing and tensile strength, with a minimum of jointing, fissuring, and bedding. Such rock would include granitic and trap rocks, quartzites, solid sandstone and shale rocks, and, in fact, most of the hard, relatively tough rocks that have little jointing, fissuring, and bedding. An excavation in such material should have a slope of about 10 on 1, or 10 units up and 1 unit



COLUMNAR STRUCTURE IN HARDENED FLOWS OF MUD-LAVA. THIS JOINTING AFFORDED PASSAGES FOR SEEPAGE WATER FROM THE OBISPO DIVERSION AND FROM GROUND WATER WHICH SOFTENED THE BASAL MASS, ALREADY UNDER HIGH PRESSURE, AND THUS TENDED TO PROMOTE THE LARGE SLIDE AT STATION 1652 SHOWN IN PLATE XXVI.

SLIDE NEAR DIVISION OFFICE, THE BUILDING ON THE LEFT, EMPIRE.

Slide is chiefly of the "fault zone" type. Office stands on ridge formed by basalt dike. The view is northward, a large fault plane, almost parallel to the dike on the north side of it, shattered the rock, which slid along the zone of crushing.

over. Slopes in such material might be left perpendicular but for the fact that blasting leaves the rocks somewhat fissured, and a small slope greatly aids in preventing sloughing. Even if the slopes are channeled, weathering after a time opens small cracks, not recognizable in the fresh rock, and from these cracked places small masses are liable to slough as time goes on.

2. Given the same kind of rock as that included in class 1, but with jointing and fissuring increased to about the average of that commonly encountered in excavations, or the average common to the kind of rock described under class 1. The slope of an excavation under such conditions should be about 7 on 1.

3. Given the same rock as included in classes 1 and 2 but with the jointing and fissuring increased to the maximum of that encountered in nature in such rocks. For such the slope should be about 3 on 1.

4. Wherever an excavation parallels bedding or fault planes that dip toward it, the rock being the same as that mentioned in class 1 and the jointing corresponding to that described under 2 or 3, then the slope is likely to be controlled by such bedding or fault planes, as follows:

(*a*) If the individual beds are a yard or more thick and if no clayey or slaty rock has formed along the bedding or fault planes, about 2 on 1 would be a safe slope.

(*b*) If the rocks are thinly bedded, and if they are shaly, clayey, or slickensided along the bedding or fault planes, 2 on 3 would represent about the maximum flatness necessary for the slope. If bedding is not rendered slippery by clay partings, a 1 on 1 slope would be quite safe.

5. For convenience, it should be mentioned here that the maximum angle of slope of sand dunes is about 1 on 2, which is practically the angle of repose for dry sand. The angle of repose for the waste dumped out of most lode mines is 37 degrees.

The above conditions pertain only to the rocks described, which will not crush or deform by flowage toward an excavation, but will only slough off fragments and masses loosened by fractures, jointing, bedding, faulting, or other causes. Under these conditions the slopes should all be approximately plane surfaces, except in the upper part, where the material is much weathered and changed into soil. Here erosion will remove some of the soft material and will tend to give a curved surface. The plane surface of the lower part of the excavation will then be tangent to the curved surface of the upper weathered material, and this latter surface will approach logarithmic curvature.

SLOPES WHERE ROCKS MAY DEFORM BY SWELLING OR FLOWAGELIKE MOTION.

The most desirable slopes to adopt where excavations cut rocks that will deform by flowage as well as by fracture are next considered.

In dealing with such rocks an entirely new set of conditions enters into the problem, because deformations or movements may extend to some depth below the excavation as well as to considerable distances from it horizontally. The swelling of ground in tunnels, especially in certain coal mines, and the shattering of marble and sandstone slabs in quarries is due to a variety of rock deformation. As already explained in this paper, certain rocks may stand at a steep angle until the excavation that they overlook reaches a depth of say 20 to 30 yards or more; then they may begin to deform and later to slide, until a flat angle is reached. For such rocks the slope that will minimize the danger of deformation and give maximum steepness and utility will be a curved surface instead of the plane surface that suffices for the more stable rocks. The reasons why the surface should be curved are as follows: (1) Earth pressures, as against a retaining wall, for instance, vary in a general way as the square of the height of the wall; (2) with increase of depth, ground water becomes more active in penetrating and softening rocks and in dissolving cementing material from them; (3) gravity stresses, helped by ground water and the element of time, cause slight movements and swellings in the rocks, and every such movement is an added weakness to the slope. Hence, if for any cross section of an excavation, especially in soft rock, the different depths were used as abscissas, and the corresponding tendency to deformation at that depth as ordinates, the plotted result would be a curve.

TABLE OF SLOPES.

The following information and the accompanying table have been given by the author in a paper read before the Twelfth International Geological Congress at Toronto, Canada.

The following are given as approximately the best curvatures and slopes to adopt for excavations in the materials described. The slopes for other materials, which fall between these, may be estimated by interpolation. A theoretical slope should first be determined according to the depth of the excavation, character of rock, etc., from the tables that follow. Then a cross section of the slope and bottom planes of the excavation, as selected, should be plotted. A hyperbola tangent to these two, with its vertex in the projection of the bottom plane, will represent about the proper slope and cur-

vature for the excavation. In all excavations, allowance must be made for the fact that the soft decayed rock and soil material near the top will tend to erode back from the excavation until the surface approaches logarithmic curvature.

The maximum angles at which certain classes of rock will stand, in open excavation at different depths, are given in the table which follows. The classes of rock mentioned in the table are designated in the paragraphs A to G.

A. Certain fairly soft and weak sandstones, shales, and a few limestones; also a few soft tuffs, agglomerates, and clay rocks—rocks that will deform under great pressure but with relative slowness. Under this heading come most of the rocks that cause swelling ground in coal mines and other excavations, but which are stronger than the clay rocks and tuffs of Culebra Cut.

B. The same rocks as included in class A, but with medium shearing and jointing.

C. The same rocks as included in classes in A and B, but with jointing, fissuring, and shearing increased to the maximum for such rocks. Also those in which the bedding may dip toward the excavation.

D. Soft volcanic-clay rocks, bedded friable tuffs, lignitic shales; rocks similar to those in the Culebra and Cucuracha formations in Culebra Cut. These are the rocks in which most of the big slides have occurred. Such rocks have a high water content and contain considerable chloritic material. They are ordinarily very fine to medium grained and may contain thin beds of partly cemented gravel, and some lenses of soft sandstone and brittle limestone. These rocks are considered as having a minimum of jointing, fissuring, and bedding.

E. The same rocks as included in class D, but with jointing, fissuring, and bedding increased to the average for such rocks. About equivalent to the conditions in Culebra Cut, except in a few localities where the Culebra Cut rocks have been excessively sheared by faulting.

F. The same rocks as included in classes D and E, but with jointing, fissuring, and bedding increased to the maximum. Under this heading would come the local areas in Culebra Cut that are crushed by faulting.

G. Any extremely soft rocks that are much crushed and rendered soft and slippery by ground water, talcose clays, etc. Most of the ground that is in motion toward Culebra Cut. Most sliding material already moving.

Table of slopes for different rocks at different depths.

Depth of excavation.		Designation of class of rock.						
Feet.	Meters.	A	B	C	D	E	F	G
33	10	50 on 10	40 on 10	30 on 10	20 on 10	12 on 10	7 on 10	5 on 10
66	20	41 on 10	33 on 10	25 on 10	17 on 10	10.3 on 10	6.1 on 10	4.2 on 10
98	30	36 on 10	28 on 10	21 on 10	15.4 on 10	9.3 on 10	5.6 on 10	3.6 on 10
131	40	32 on 10	25 on 10	19 on 10	14.4 on 10	8.6 on 10	5.2 on 10	3.2 on 10
164	50	29 on 10	22 on 10	16 on 10	18.5 on 10	8 on 10	4.9 on 10	2.8 on 10
197	60	26 on 10	19 on 10	14 on 10	12.7 on 10	7.5 on 10	4.6 on 10	2.5 on 10
230	70	24 on 10	18 on 10	13 on 10	12 on 10	7.2 on 10	4.4 on 10	2.2 on 10
262	80	23 on 10	16 on 10	12 on 10	11.4 on 10	6.8 on 10	4.2 on 10	2 on 10
295	90	21 on 10	15 on 10	11 on 10	10.8 on 10	6.5 on 10	4 on 10	1.9 on 10
328	100	20 on 10	14 on 10	10 on 10	10.2 on 10	5.2 on 10	3.9 on 10	1.8 on 10
361	110	18 on 10	13 on 10	9.8 on 10	9.5 on 10	6 on 10	3.8 on 10	1.7 on 10
394	120	17 on 10	12.5 on 10	9.3 on 10	8.7 on 10	5.9 on 10	3.7 on 10	1.6 on 10
427	130	16 on 10	12 on 10	9 on 10	8 on 10	5.8 on 10	3.6 on 10	1.5 on 10
459	140	15 on 10	11.5 on 10	8.8 on 10	7.4 on 10	5.6 on 10	3.5 on 10	....
492	150	14.5 on 10	11 on 10	8.6 on 10	6.8 on 10	5.5 on 10	3.4 on 10	1.4 on 10
525	160	14 on 10	10.8 on 10	8.4 on 10	6.5 on 10	5.4 on 10	3.3 on 10	....
558	170	13.5 on 10	10.5 on 10	8.3 on 10	6.3 on 10	5.3 on 10	3.2 on 10	1.3 on 10
591	180	13 on 10	10.3 on 10	8.2 on 10	6.2 on 10	5.2 on 10	3.1 on 10	....
623	190	12.5 on 10	10.1 on 10	8.1 on 10	6.1 on 10	5.1 on 10	3.05 on 10	....
656	200	12 on 10	10 on 10	8 on 10	6 on 10	5 on 10	3 on 10	1.2 on 10

NOTE.—The slope given for each depth in the above table is to extend from the bottom to the top of the excavation at the same angle (plus hyperbolic curvature tangent to the slope and bottom, as already explained). If an excavation is 200 meters deep in class A rocks, its slope is to be 12 on 10, plus curvature, from bottom to top, and not 50 on 10 for the first 10 meters, 41 on 10 for the second, and so on.

Heavy blasting should not be used right up to the completed slopes if they are to stand at the angles given above.

When ground once begins to deform, the angle at which it will stand will be much flatter than that at which it would have stood before movement set in.

In any given excavation the weakest rock encountered will govern the slope for that excavation.

BIBLIOGRAPHY ON SLIDES.

The following bibliography, with a few additions by the author, is taken from a paper[a] by George S. Rice, chief mining engineer of the Bureau of Mines:

BAUMGARTEN, KARL. Thunder Mountain landslide. Min. and Sci. Press, vol. 101, Nov. 26, 1910, pp. 698–699.

CANADA, DEPARTMENT OF INTERIOR. Report on the great landslide at Frank, Alberta. Annual Report, 1903, pt. 8, appendix to Rept. of Supt. of Mines, 17 pp.

CANADA, DEPARTMENT OF MINES, GEOLOGICAL SURVEY BRANCH. Report of the commission appointed to investigate Turtle Mountain, Frank, Alberta, 1911, p. 34.

CLARKE, D. D. A phenomenal landslide. Trans. Am. Soc. Civ. Eng., vol. 53, December, 1904, pp. 322–412.

CORNISH, VAUGHAN. The Panama Canal and the philosophy of landslides. Edinburgh Rev., vol. 217, January, 1913, pp. 21–42.

ELLS, R. W. Report on the landslide at Notre Dame de la Salette, Lievre River, Quebec. Canada, Department of Mines, Geological Survey Branch Publications, No. 1030, 1908, 10 pp.

ENGINEERING NEWS. A novel method of stopping a landslide at Seattle, Wash. Vol. 31, May 10, 1894, p. 387.

——— The slides on the Panama Canal. Vol. 65, May 11, 1911, pp. 570–573.

FORD, F. L. The settlement of Loraine Street, Hartford, Conn. Eng. Record, vol. 45, Feb. 22, 1902, pp. 172–173.

[a] A suggested method of preventing rock slides. Discussion. Jour. West. Soc. Eng., vol. 18, No. 7, September, 1913, pp. 585–627.

GAILLARD, D. D. Culebra Cut and the problem of the slides. Sci. Am., vol. 107, Nov. 9, 1912, pp. 388–390.

HOWE, ERNEST. Landslides in the San Juan Mountains, Colo., including a consideration of their causes and their classification. U. S. Geological Survey Prof. Paper 67, 1909, 58 pp.

ISAACS, J. D. Stopping a troublesome slide at a summit tunnel. Jour. Assn. Eng. Soc., vol. 15, September, 1895, pp. 113–123.

MACDONALD, D. F. Excavation deformations. Trans. 12th Int. Geol. Cong., 1913, Ottawa, Canada.

——— Slides in the Culebra Cut at Panama. A review of geological conditions in the canal site, together with a description of the types of slides and their causes. Eng. Record, vol. 66, Aug. 31, 1912, pp. 228–233.

——— Sliding ground in Culebra Cut. Eng. News, vol. 70, No. 9, Aug. 28, 1913, p. 408.

——— The landslides of Culebra Cut. Annual Report of Isthmian Canal Commission, 1912, pp. 205–214.

MERRICK, A. W. The clay slide at the Boone Viaduct, Boone, Iowa. Jour. West. Soc. Eng., vol. 11, June, 1906, pp. 332–339.

MITCHELL, G. E. Landslides and rock avalanches. Nat. Geographic Mag., vol. 21, April, 1910, pp. 277–287.

MOLITOR, DAVID. Landslides. Jour. Assn. Eng. Soc., vol. 13, January, 1894, pp. 12–32.

RICE, G. S. A suggested method of preventing rock slides. Discussion. Jour. West. Soc. Eng., vol. 18, No. 7, September, 1913.

ROHWER, H. Discussion on earth slides. Am. Ry. Eng. and Maintenance of Way Assn. Bull. 90, August, 1907, pp. 4–10.

——— Earth slides. Eng. Record, vol. 56, Oct. 5, 1907, pp. 374–375.

RUSSELL, I. C. Landslides. Part of a preliminary paper on the geology of the Cascade Mountains in northern Washington. U. S. Geol. Survey Ann. Rept., 1898–99, pt. 2, pp. 193–204.

ENGINEERING RECORD. The railway landslide at Cleveland. Vol. 48, Nov. 14, 1903, p. 584.

VAN HORN, F. R. Landslide accompanied by buckling, and its relation to local anticlinal folds. Geol. Soc. America Bull., vol. 20, 1910, pp. 625–632.

ZINN, A. S. The truth about the Culebra Cut slides, Panama Canal. Eng. News, vol. 70, Aug. 28, 1913, pp. 406–408.

HEATING OF LOCAL AREAS OF GROUND IN CULEBRA CUT.

Under date of February 12, 1912, Col. D. D. Gaillard, the division engineer of the central division, reported to Col. G. W. Goethals, the chief engineer, as follows regarding heated material on the west side of Culebra Cut at Culebra:

ENGINEER'S REPORT OF CONDITIONS.

A little less than three weeks ago I noticed that the material, which consisted of stratified, sedimentary rock, among which there appeared some lignite of a low grade, was sending up in the early morning quite a thick cloud of white steam or vapor. I examined the spot a day or two afterwards and found that for a width of about 20 feet, a length of about 100 feet, and a depth of about 15 feet the entire mass of material recently blasted appeared to be heated to a considerable temperature. Steam was escaping from numerous small openings and from four principal vents or openings; the smallest of the four being about 3 inches in diameter, and the largest about 1 foot.

The temperature was so high that the hand could not be held at the mouth of the larger openings for more than a second or two, and when withdrawn was quite moist, showing quite unmistakably the presence of steam or heated vapor. The sides of two of the vents were incrusted both with white and yellow powdered material, the yellow appearing to be sulphur. What the white powder was I am unable to state.

I have observed this locality almost daily for over two weeks, and within the past four or five days there has been quite a change in two important characteristics. The temperature has increased and a pale-blue smoke, instead of steam, is now emerging from the vents. The odor of sulphuric acid, which was very marked when only steam was emerging, is fully as marked to-day. To give an idea of the temperature of the larger vent I took a 9-inch brown manila envelope and held it at the mouth of the largest vent for three seconds, when it was totally destroyed, although it did not ignite in flame. I then took a piece of the white-pine covering of a dynamite box and held it for three minutes within the mouth of the largest vent and on withdrawing it it was completely charred, so that another three or four minutes exposure would probably have carbonized it completely. * * *

I would respectfully recommend that the commission geologist be requested to make a careful examination and submit, as promptly as possible, a report on this matter, as it is one of great interest to the work and undoubtedly concerns the safety of our men who are handling dynamite. As you may recall, we have had premature explosions in the past on at least two occasions due to chemical heating of the rock, and I am convinced that the material which I have described was hot enough to have readily fired dynamite at any time within the past three weeks.

GEOLOGIST'S REPORT.

In accordance with the above recommendation the writer made an investigation, and reported as follows:

The marl shales, through which Culebra Cut extends, in the region opposite the Culebra railway station, have, from time to time, on exposure to the atmosphere, become hot. The intensity of this heat has varied from noticeably warm to a temperature sufficient to readily char wood, without, however, causing it to burst into a flame. The duration of this heating has varied in the several areas from a few days to several weeks. These shales are dark, thin-bedded, soft, and easily crumbled, and some of the layers are largely fine basic tuff, or volcanic ash, loosely cemented by lime. Other beds contain more carbonaceous material, with some local partings of lignite, an inch to a foot or more thick. The most easily weathered minerals of which these rocks are composed have been but little acted on by the atmosphere, and this, together with their composition, is evidence that they were derived from nearby volcanic mountains and deposited as a succession of thin beds in a shallow estuary of the sea, which extended across the Isthmus at that time. That this material was originally deposited in water is known from its clearly stratified condition; that the water was shallow is evidenced by fragments of fossil plants and thin beds of lignitic shale, indicating swamp conditions, which are interbedded in it; and that the water was an arm of the sea is demonstrated by the fossilized marine animals, such as oysters, corals, pelecypods, and foraminifera, which it contains. The time when these conditions existed is known in geology as the early Tertiary or Oligocene period of earth history, and the fossilized animals of that period have certain specific marks, by which the specialist may distinguish them from animals of earlier and of later time.

HEATING SUBSEQUENT TO DRILLING OR BLASTING.

After exposure to the atmosphere by drilling or blasting certain local areas of this formation in the course of a few hours or days became warm, and as the heating goes on the carbonaceous matter in the shales gradually oxidizes and they tend to assume a gray

to dull-reddish color. The first hypothesis entertained, in looking toward a solution of the heating, was that possibly the heavy blasting had furnished heat enough to break down the calcium carbonate present to the oxide form, and that ground water and atmospheric moisture reacted on this to slake it and thus probably generate sufficient heat to start the oxidation of the carbonaceous material. This hypothesis was, however, rendered untenable by three lines of evidence:

(1) The heating was much more local than the calcium carbonate and the carbonaceous matter.

(2) The heating bore no definite relation to the lime and carbon content of particular beds.

(3) Col. Gaillard has observed that in some instances the heating began in the holes some time after they had been drilled, but before the ground had been blasted at all.

PYRITE AS A CAUSE OF HEATING.

Another line of inquiry was suggested by finding a small amount of pyrite in some of the beds which were heating. It was suspected that this, through its oxidation, was a factor in furnishing the initial heat of the action. In April, 1911, samples of the beds then heating were sent to the chemical laboratory of the United States Geological Survey with request to make qualitative tests for sulphur and other products that might serve, through oxidation, as the mainspring of the action. These tests revealed the presence of sulphuric acid to the amount of 1.92 per cent, also minute crystals of gypsum. This was in confirmation of the hypothesis that pointed to the pyrite present as the substance acted on by atmospheric oxygen to develop the initial heat.

NOTEWORTHY EXAMPLE OF HEATING.

The most aggravated case of heating so far noted is now going on in Culebra Cut about 350 yards north of the foot of the stairs at the observation tower near Culebra station. The mass of heated ground here is about 500 feet long by 20 feet wide, and the action reaches a depth of perhaps 15 or 20 feet. Blue smoke, which contains a high percentage of sulphur dioxide, issues from vents in the mass, and fragments of wood inserted in these are readily charred and consumed. A small amount of steam may also be detected emanating from local moist spots, but this is mainly due to the vaporization of ground water. In the investigation of this heated mass samples were taken, and these were tested qualitively for sulphuric acid and for sulphates of calcium, aluminum, and magnesium. The tests were made by Mr. Jacob, of the hospital laboratory staff at Ancon, and they revealed the presence of all of the above substances, both in the shale and as the white coating on the moist spots and steam vents of the mass. The yellow deposit near the larger vents is sulphur. Sulphuric acid especially was shown to be present in considerable quantity. The origin of the sulphuric acid here was at first a puzzle, because the examination of many samples, with the naked eye and with the microscope, failed to reveal the presence of pyrite. Finally samples of 8 to 10 pounds were taken, ground with water in a large mortar for some minutes, and then concentrated to a few ounces by washing or "panning." This concentrate showed a high content of pyrite, much of which was so fine that it could scarcely be seen with the naked eye. Under the microscope very small crystals of pyrite were noted; also considerable magnetite, present as black sand, and some subangular to fairly rounded grains of quartz.

The mainspring of the action here, then, as in the other instances observed, has undoubtedly been the oxidation of the pyrite. The reasons why this oxidation has been so rapid and effective seem to be as follows:

(*a*) The finely divided, almost microscopic, character of the pyrite gives maximum surface exposure to atmospheric agencies and greatly promotes oxidation.

(*b*) The very warm, moist atmosphere. The tropical sun produces a temperature sufficiently high to greatly promote oxidation, especially in the presence of slight moisture.

(*c*) Once oxidation of the pyrite has been started the heat thus generated tends to accelerate chemical action, and thus the heating increases in geometric progression.

(*d*) When the heat of pyrite oxidation reaches the comparatively low temperature of oxidation of the hydrocarbons present in the lignitic shale, they, too, become oxidized and still further add to the temperature. Finally the fixed-carbon content tends to become oxidized, at least in part, and gives maximum intensity to the action.

(*e*) Some heat is also generated by the action of the free sulphuric acid on the calcium carbonate for the formation of gypsum. Other minor chemical actions added their quota to the total heat.

As the temperature rises, all chemical activity is vastly stimulated and the heating increases to a maximum. After the most readily oxidizable substances are consumed the heat gradually dies down toward normal temperaturse, which may be reached in a few weeks or months. The intensity and duration of the heat depend largely upon the percentage of finely divided pyrite, volatile matter, and fixed carbon in the rocks.

In order to alleviate the danger of premature explosion from loading dynamite in holes which have become hot, Col. Gaillard has inaugurated the practice of testing holes in the vicinity of the heating areas, by dropping into them a small iron pipe longer than the hole. This is withdrawn at the end of 10 minutes and quickly passed through the hand. In this way not only is heating detected but the location of the heated zone with respect to the depth of the hole is also made known; for the heating is at times only local and may be at, or well above the bottom of the hole.

Certain geologic considerations have been suggested by a study of this heating phenomenon, the chief of which are:

(*a*) Chemico-thermal springs. Whenever jointing, fissuring, or change of groundwater level gives free access of oxygen-bearing surface waters to beds that contain the necessary finely divided pyrite and carbonaceous matter, heating of such beds is likely to result. Ground water flowing over such heated beds and coming to the surface in the general vicinity of them would constitute thermal, or hot, springs.

(*b*) The very fine pyrite sparingly disseminated through the carbonaceous shales herein described seems to have resulted from the action of sulphur, segregated from decaying animal and vegetable life, on the ferromagnesian silicate fragments that are abundant in these sediments.

EARTHQUAKES AS AN ELEMENT OF DANGER TO THE CANAL.

The earthquake belts of Central and South America are approximately coextensive with the regions of fairly high mountains. Within the Canal Zone only two peaks reach elevations approximating 1,000 feet. There are no peaks within 20 miles of the canal that are higher than 2,000 feet, and not within 100 miles could one find mountains over 4,000 feet in elevation. The canal is therefore far removed from the great mountain masses—those that, by their settling and adjustment, might cause stresses that would culminate in rock ruptures sufficiently great to give destructive earth vibrations. Furthermore, the relative weakness of most of the rocks within the Canal Zone region prohibits the accumulation of stresses sufficiently great to cause violent rock rupture with concomitant earth jars of destructive proportions. Theoretically, then, one would expect the Canal Zone to be outside the Central American earthquake belt. Such a con-

clusion is quite in accordance with the observations set forth in a long and fairly complete record [a] of the earthquakes that have occurred from the time of the Spanish conquest to the year 1886.

In all that time only two severe shocks were noted; one of these, in 1621, destroyed many of the buildings in Panama, and one in 1882 damaged several buildings and bridges, and, locally, threw the railway track out of alignment. In Colon the latter quake is said to have opened a few crevices and to have been attended with some fatalities. Many smaller shocks have occurred and since the installation of seismographs by the Isthmian Canal Commission numerous tremors, most of which are detectable only by the instrument, are recorded every month. At one time it was thought that the canal was liable to injury or destructions from earthquakes, but the fact is that no earthquake since 1621 would have seriously damaged it, and the shock of that year, though severe enough to shake down adobe houses, and even some masonry structures, would have had no serious effect on canal slopes and little effect on such rock-founded concrete structures as the locks. In support of this assertion the relatively little effect of the San Francisco earthquake on the new steel reinforced concrete buildings may be cited; and, of course, the locks are more solid than any building. On October 1, 1913, a fairly severe earthquake shock was felt on the Canal Zone. Its local intensity was estimated at V or VI on the Rossi-Forrell scale, which runs from I to X. In spite of the fact that some of the people were alarmed by the shaking of the houses, the quake had not the slightest effect on any part of the canal. A second shock, only slightly less intense, was felt on October 23, and this likewise failed to disturb even the most delicate adjustment of the lock machinery. Both these shocks were much heavier 100 miles southwest of Panama City than they were within the Canal Zone.

Though it is not impossible that a destructive earthquake might visit the canal, still it is extremely improbable. In summary, then, the following are the chief reasons why it is believed the canal will never be in any appreciable danger from earthquakes:

1. The large number of tremors detected every month by the recording instruments is evidence that slow adjustments are constantly taking place and thus that no great accumulations of stress that might later culminate in a big shock are probable.

2. The absence from the Isthmus region of high mountains and of geologically recent volcanic activity is evidence in favor of the probable absence of earthquakes, especially as such high mountains are a striking geologic feature of the whole Central American earthquake belt.

3. The presence of numerous small faults and of the faulted conditions of such volcanic cores as Gold Hill and Contractors Hill is

[a] De Ballore, F. de M., Tremblements de terre et eruptions. Volcaniques au Centre-Amerique. Soc. des Sciences Naturelles de Saone-et-Loir. 1888, p. 61.

evidence that adjustment here has progressed well on toward normal conditions of equilibrium.

4. The tensile strength of the majority of the rocks within the Canal Zone is rather low, and they would shear with comparative ease, thus preventing any relatively great accumulation of stress that might result in a comparatively intense shock. However, experience teaches that where earthquakes happen the buildings suffering the maximum destructive effects are those built on loose and friable material. This consideration might therefore subtract a little from the saving benefits of the yielding and preventative qualities of the Canal Zone rocks.

5. Over 300 years of earthquake observation shows only two shocks of considerable magnitude, and there is every reason to believe that the severest of these would not have seriously damaged even the most delicate parts of the canal.

That many small and harmless shocks will traverse the Canal Zone is certain, but that the canal is in any real danger from earthquakes is contrary to all the evidence.

COST OF CONSTRUCTION.[a]

DRY EXCAVATION IN ATLANTIC, CENTRAL, AND PACIFIC DIVISIONS.

The itemized cost of dry excavation in the Atlantic, Central, and Pacific Divisions for the fiscal year ended June 30, 1912, was as follows:

Cost per cubic yard of dry excavation for prism, Atlantic, Central, and Pacific Divisions, for fiscal year ended June 30, 1912.

Item.	Atlantic Division.[a]	Central Division.[b]	Pacific Division.[c]
Clearing	....	\$0.0001	\$0.0027
Drilling	\$0.0174	.0535	.0825
Blasting	.0494	.0622	.0413
Loading	.0564	.0492	.1116
Tracks	.0487	.0885	.1359
Transportation	.1280	.0734	.0637
Dumps	....	.0423	.0043
Pumps	.0202	.0041	.0377
Maintenance of equipment	.0754	.0843	.0740
Plant, arbitrary	.1814	.0394	.1762
Division expense	.0183	.0145	.0228
Total division cost	.5952	.5115	.7527
Administrative and general expenses	.0406	.0364	.0432
Total cost	.6358	.5479	.7959

[a] Total dry excavation, 424,872 cubic yards.
[b] Total dry excavation, 16,917,662 cubic yards.
[c] Total dry excavation, 864,475 cubic yards.

STONE FROM ANCON AND PORTO BELLO QUARRIES.

The tables following give the itemized cost of the production of stone and crushed rock from both the Ancon and the Porto Bello quarries. It will be noted that the cost of blasting, loading, and

[a] The cost figures given herein are taken largely from the annual reports of the Isthmian Canal Commission.

crushing per cubic yard of product is much less at the Ancon than at the Porto Bello quarry. This difference is due to the fact, as already explained, that the Ancon rock is cut by many joint planes, which cause it to fall apart into relatively small fragments on blasting. The Porto Bello rock, on the other hand, has few joints, and therefore blasts out with many great coarse fragments, which have to be broken by adobe blasting, thus increasing the blasting cost as well as the loading and crushing charges. Of course the relatively long water haul and the reloading on cars, for transportation to the place of storage and use, adds much to the final cost of the Porto Bello rock.

Cost of stone production from the Ancon and Porto Bello quarries, fiscal years 1911 and 1912.

Item.	Atlantic Division, Porto Bello quarry.		Pacific Division, Ancon quarry.	
	1912	1911	1912	1911
Crushed stone produced, cubic yards	440,413	864,033	839,279	855,824
Quarrying:				
Stripping	$0.0040	$0.0174	$0.0423	$0.0476
Drilling	.0431	.0450	.0552	.0449
Blasting	.1622	.1980	.0465	.0421
Loading	.0774	.0921	.0356	.0452
Transportation	.0669	.0758	.0576	.0727
Tracks	.0340	.0464	.0379	.0243
Power	.0353	.0289		
Maintenance of equipment	.0621	.0981	.0568	.0333
Plant, arbitrary	.4897	.3350	.1903	.2447
Total	.9747	.9367	.5222	.5548
Crushing:				
Operation of crushers	.0283	.0355	.0179	.0172
Stone bins and conveyors	.0168	.0311	.0045	.0045
Power	.0462	.0394	.0187	.0183
Maintenance of equipment	.0827	.1158	.0311	.0175
Plant, arbitrary	.2524	.1726	.0592	.0762
Total	.4264	.3944	.1314	.1337
Total division expense	.0269	.0551	.0184	.0228
Total cost of production	1.4280	1.3862	.6720	.7113
Towing:				
Operation of tugs and barges	.1557	.1592		
Maintenance of equipment	.1267	.1063		
Plant, arbitrary	.1794	.1975		
Total	.4618	.4630		
Unloading:				
Operation of cableways and cranes	.0987	.1168		
Power	.0608	.0195		
Maintenance of equipment	.0224	.0929		
Plant, arbitrary	.3441	.2050		
Total	.5260	.4342		
Rail transportation to storage:				
Cubic yards transported	139,167	275,148	839,279	855,824
Operation of trains	$0.1297	$0.0819	$0.0366	$0.0447
Repairs to tracks	.0194	.0142	.0004	.0075
Dumping in storage		.0155	.0110	.0098
Maintenance of equipment	.1022	.0672	.0206	.0157
Plant, arbitrary			.0590	.0553
Total	.2513	.1788	.1276	.1330
Total cost of storage	2.4952	2.3403	.7996	.8443

BREAKWATERS.

The Naos Island breakwater was charged with the difference between the cost of dumping material on some of the spoil banks near Balboa and the cost of placing it in the breakwater, including the charge for tracks, trestles, etc. During the fiscal year 1913, 653,137 cubic yards of material was placed in the breakwater, at an average cost of $0.2934 per cubic yard.

During the fiscal year ended June 30, 1912, 460,040 cubic yards of hearting rock from Toro Point was placed in the Colon breakwater, at an average division cost of $1.3832 per cubic yard, including, of course, cost of quarrying, loading, transportation, and tracks and trestle out onto the breakwater.

In addition to the soft heart material, hard coarse rock had to be used to face or armor the breakwater. This was procured at the Porto Bello quarry, a detailed statement of the cost being as follows:

Detailed statement of cost of procuring coarse rock from the Porto Bello quarry for the Colon breakwater, 1912.

Quantity of rock quarried, cubic yards	183, 762
Cost per cubic yard:	
Stripping	$0. 4178
Drilling	. 1087
Blasting	. 2259
Loading	. 1278
Transportation	. 1427
Tracks	. 3662
Loading on barges	. 1956
Power	. 1257
Maintenance of equipment	. 6287
Plant, arbitrary	. 3203
Total per cubic yard	2. 6594
Cost of towing, per cubic yard:	
Operation of tugs and barges	. 2829
Maintenance of equipment	. 1780
Plant, arbitrary	. 3916
Total	. 8525
Cost of placing material, per cubic yard:	
Operation of floating derricks	. 1716
Maintenance of floating derricks	. 0932
Operation of cranes	. 1562
Operation of trains	. 0741
Dumping	. 0143
Maintenance of equipment	. 1453
Plant, arbitrary	. 1553
Total	. 8100

Cost of trestles, per cubic yard	$0.1753
Cost of tug service, miscellaneous, per cubic yard	.0840
Cost of maintenance of equipment, miscellaneous, per cubic yard	.0393
Division expense, per cubic yard	.2045
Total division cost, per cubic yard	4.8250
Administrative and general expenses, per cubic yard	.4056
Total cost, large rock, per cubic yard	5.2306

SAND.

A comparative statement of the cost of sand on the Atlantic and on the Pacific sides follows:

Cost of sand for the canal during the fiscal years 1911 and 1912.

Item.	Atlantic Division, Nombre de Dios.		Pacific Division, Chame.	
	1912	1911	1912	1911
Quantity of sand obtained:				
By excavation, cubic yards	....	29,539	....	....
Cost	....	$0.7975	....	....
By dredging, cubic yards	144,123	412,380	564,837	494,841
Cost of operation of dredges	$0.1913	$0.2444	$0.0905	$0.0926
Cost of maintenance and equipment	.1309	.1010	.0403	.0354
Total	.3222	.3454	.1308	.1280
Total production, cubic yards	144,123	441,919	564,837	494,841
Operating cost, per cubic yard	$0.3222	$0.3756	$0.1308	$0.1280
Cost of plant, arbitrary, per cubic yard	.7890	.4740	.0202	.0300
Division expense, per cubic yard	.0096	.0299	.0137	.0208
Total cost of production, per cubic yard	1.1208	.8795	.1647	.1788
Cost of towing, per cubic yard:				
Operation of tugs and barges	.2235	.2084	.0936	.1067
Maintenance of equipment	.1311	.1130	.0493	.0553
Plant, arbitrary	.2820	.2209	.0309	.0649
Total	.6366	.5423	.1738	.2269
Cost of unloading, per cubic yard:				
Operation of cableways and cranes	.1027	.1189	.0646	.0532
Power	.0189	.0188	.0196	.0284
Maintenance of equipment	.0712	.0782	.0335	.0599
Plant, arbitrary	.2170	.1496	.0545	.1067
Total	.4098	.3655	.1722	.2482
Rail transportation to storage:				
Quantity transported, cubic yards	60,494	157,967	564,837	475,422
Cost of operation of trains	$0.0993	$0.0982	$0.0403	$0.0462
Cost of repairs to tracks	.0096	.0163	.0369	.0197
Cost of dumping storage	....	.0002	.0120	.0134
Cost of maintenance of equipment	.0677	.0787	.0241	.0174
Cost of plant, arbitrary	....	....	.0785	.0849
Total	.1766	.1934	.1918	.1816
Total cost of storage	2.2414	1.8565	.7025	.8284

MASONRY.

The costs of masonry for the canal up to June 30, 1912, was as follows:

Cost of masonry for the canal up to June 30, 1912.[a]

Item.	Atlantic Division, Gatun Locks.	Pacific Division, Pedro Miguel Locks.	Pacific Division, Miraflores Locks.
Concrete, cubic yards	376,417	134,193	729,096
Cost per cubic yard of—			
Cement	$1.5332	$1.6564	$1.7920
Stone	1.9946	.7619	.7464
Sand	1.0128	.3823	.3564
Mixing	.1798	.3562	.2258
Total cost per cubic yard	4.7204	3.1568	3.1206
Large rock, cubic yards	14,194	....	....
Cost per cubic yard	$1.3283	....	....
Masonry, cubic yards	390,611	134,193	729,096
Cost per cubic yard of—			
Concrete	$4.5478	$3.1568	$3.1206
Large rock	.0483	....	....
Wood forms	.5077	.7596	.4030
Steel forms	.1502	.0041	.0364
Placing	.4788	.5619	.2014
Reinforcements	.0173	.0074	.0012
Pumps	.0878	.0331	.0327
Power	.0834	.0199	.0289
Cofferdams	....	....	....
Maintenance of equipment	.2109	.1511	.1545
Plant, arbitrary	.8980	.9101	.5420
Division expense	.1015	.1143	.0660
Total division cost per cubic yard	7.1317	5.7183	4.5867
Administrative and general expenditures per cubic yard	.2643	.3085	.2240
Total cost per cubic yard	7.3960	6.0268	4.8107
Masonry, reinforced, cubic yards	59,883	48,677	22,444
Cost per cubic yard of—			
Cement	$2.2111	$2.2715	$2.0051
Stone	1.9930	.7133	.7222
Sand	1.0381	.3282	.3236
Mixing	.5855	.4112	.8380
Wood forms	2.8307	1.6959	2.2615
Steel forms	.1281	....	.7138
Power	.0324	.0085	.0080
Placing	.7385	.7087	.8883
Reinforcements	.8623	1.3263	1.7997
Pumps	.0014	.0197	.1257
Maintenance of equipment	.2033	.1198	.0931
Plant, arbitrary	.9281	.6923	.5487
Division expense	.2703	.2241	.3111
Total division cost per cubic yard	11.8228	8.5195	10.6388
Administrative and general expenditures per cubic yard	.8367	.6443	.8172
Total cost per cubic yard	12.6595	9.1638	11.4560
Total masonry, cubic yards	450,494	182,870	751,540
Total cost per cubic yard	$8.0956	$6.8618	$5.0091

[a] The masonry of the spillway at Gatun is not covered in this table. Its total cost averaged $7.5173 per cubic yard.

EXCAVATION AND CONSTRUCTION.

Data on the amount of ground moved and on the different costs of moving it are given in the table following. A few hundred thousand cubic yards, over and above that shown in the table, was excavated for building and other foundations at a cost of $1 to more than $2 per cubic yard.

Data on canal excavation, May 4, 1904, to June 30, 1914.

ATLANTIC DIVISION.

Item.	Material excavated.	Cost.
	Cubic yards.	*Cents.*
Dry excavation:		
Prism	2,181,998	0.6746
Gatun Spillway	1,544,202	.7131
Gatun Locks	4,660,055	.6776
Hydraulic excavation:		
Prism	29,605	.3942
Dredging:		
Prism	39,032,400	.2325
Gatun Dam	38,425	.5216
Gatun Locks	1,756,977	.3198

CENTRAL DIVISION.

Item.	Material excavated.	Cost.
Dry excavation	110,261,883	0.7800
Dredging	3,993,532	.5280
Hydraulic excavation	1,441,729	.2179

PACIFIC DIVISION.

Item.	Material excavated.	Cost.
Dry excavation:		
Prism	4,819,969	0.7287
Pedro Miguel Locks	1,133,280	.9136
Miraflores East Dam	242,399	1.3518
Miraflores Locks	2,222,582	.9302
Dredging:		
Prism	40,122,287	.2582
Miraflores Locks	309,647	.4598
Inner basin	3,698,781	.1754
Hydraulic excavation:		
Prism	1,549,904	.7233
Miraflores Locks	332,703	.5870

SOME SIGNIFICANT FACTS.

In order to visualize to some extent the meaning of the vast figures of yardage, etc., that have been presented, it may be well to summarize here some statements taken from an article by Gaillard.[a]

If all the material excavated from the canal were loaded on flat cars, and if these cars were coupled together into one train, that train would be long enough to encircle the earth four times. The excavation work done on the Isthmus is equivalent to the excavation necessary to dig a canal 55 feet wide on top, 10 feet deep, and with natural slopes, from the Pacific coast clear across the United States to Boston. If

[a] Gaillard, D. D., Culebra Cut and the problems of the slides: Sci. Am., vol. 107, Nov. 9, 1912, pp. 391,405.

the total number of holes drilled were arranged as one continuous hole, it would be long enough to pass through the center of the earth. The amount of concrete used in the locks and dams, about 4,500,000 cubic yards, would make a pyramid 400 feet high, with a base 960 feet square. The maximum number of drills in actual use at any one time in Culebra Cut alone was 377, of which 221 were tripod drills and 156 well drills. With these over 90 miles of holes have been drilled in a single month. Drill holes were normally placed about 14 feet apart, and their usual depth was about 27 feet, or 3 feet deeper than the shovel excavation extended. The greatest number of steam shovels at any one time in the cut was 43, and the greatest monthly excavation was made in March, 1911, when 1,728,748 cubic yards of material, mostly rock, was excavated. To handle this required 115 locomotives and 2,000 cars, or about 160 loaded trains per day. Through Culebra Cut for excavation purposes there were 9 parallel tracks, or about 100 miles of track in the 9 miles of the cut. The deepest excavation is at Gold Hill, where the topmost part of the slope is 494 feet above the bottom of the canal. In Culebra Cut the blasting operations necessitated about 1 pound of 45 per cent potassium nitrate dynamite to every 2¼ cubic yards of material.

PUBLICATIONS ON METHODS OF MINING.

Limited editions of the following Bureau of Mines publications are temporarily available for free distribution. Requests for all publications can not be granted, and applicants should select only those publications that are of especial interest to them. All requests for publications should be addressed to the Director, Bureau of Mines, Washington, D. C.

BULLETIN 10. The use of permissible explosives, by J. J. Rutledge and Clarence Hall. 1912. 34 pp., 5 pls., 4 figs.

BULLETIN 17. A primer on explosives for coal miners, by C. E. Munroe and Clarence Hall. 61 pp., 10 pls., 12 figs. Reprint of United States Geological Survey Bulletin 423.

BULLETIN 45. Sand available for filling mine workings in the northern anthracite coal basin of Pennsylvania, by N. H. Darton. 1913. 33 pp., 8 pls., 5 figs.

BULLETIN 48. The selection of explosives used in engineering and mining operations, by Clarence Hall and S. P. Howell. 1913. 50 pp., 3 pls., 7 figs.

BULLETIN 53. Mining and treatment of feldspar and kaolin in the southern Appalachian region, by A. S. Watts. 1913. 170 pp., 16 pls., 12 figs.

BULLETIN 60. Hydraulic mine filling; its use in the Pennsylvania anthracite fields; a preliminary report, by Charles Enzian. 1913. 77 pp., 3 pls., 12 figs.

BULLETIN 69. Coal-mine accidents in the United States and foreign countries, compiled by F. W. Horton. 1913. 102 pp., 3 pls., 40 figs.

BULLETIN 75. Rules and regulations for metal mines, by W. R. Ingalls and others. 1915. 285 pp., 1 fig.

BULLETIN 80. A primer on explosives for metal miners and quarrymen, by C. E. Munroe and Clarence Hall. 1915. 125 pp., 15 pls., 17 figs.

TECHNICAL PAPER 18. Magazines and thaw houses for explosives, by Clarence Hall and S. P. Howell. 1912. 34 pp., 1 pl., 5 figs.

TECHNICAL PAPER 21. The prevention of mine explosions, report and recommendations, by Victor Watteyne, Carl Meissner, and Arthur Desborough. 12 pp. Reprint of United States Geological Survey Bulletin 369.

TECHNICAL PAPER 22. Electrical symbols for mine maps, by H. H. Clark. 1912. 11 pp., 8 figs.

TECHNICAL PAPER 24. Mine fires, a preliminary study, by G. S. Rice. 1912. 51 pp., 1 fig.

TECHNICAL PAPER 29. Training with mine rescue breathing apparatus, by J. W. Paul. 1912. 16 pp.

TECHNICAL PAPER 30. Mine-accident prevention at Lake Superior iron mines, by D. E. Woodbridge. 1913. 38 pp., 9 figs.

TECHNICAL PAPER 11. Mining and treatment of lead and zinc ores in the Joplin district, Mo., a preliminary report by C. A. Wright. 1913. 63 pp., 5 figs.

TECHNICAL PAPER 59. Fires in Lake Superior iron mines, by Edwin Higgins. 1913. 34 pp., 2 pls.

TECHNICAL PAPER 84. Methods of preventing and limiting explosions in coal mines, by G. S. Rice and L. M. Jones. 1915. 45 pp., 14 pls., 3 figs.

TECHNICAL PAPER 95. Mining and milling of lead and zinc ores in the Joplin district, Wisconsin, by C. A. Wright. 1915. 39 pp., 2 pls., 5 figs.

TECHNICAL PAPER 100. Permissible explosives tested prior to March 1, 1915, by S. P. Howell. 1915. 16 pp.

TECHNICAL PAPER 111. Safety in stone quarrying, by O. P. Bowles. 1915. 48 pp., 5 pls., 4 figs.

INDEX.

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